Design Description for INL Supercritical Water Heat Transfer Test Section for Inclusion into the Benson Loop

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1. Introduction

The International Generation IV program is striving to develop and demonstrate one or more innovative nuclear energy systems that offer advantages in the area of economics, sustainability, safety and reliability and could be deployed by 2030. The supercritical-water-cooled reactor (SCWR) was selected as one of the concepts for further evaluation and development.

Supercritical water-cooled reactors are among the most promising advanced nuclear systems because of their high thermal efficiency (i.e., about 45% vs. 33% for current light water reactors) and considerable plant simplification. SCWRs achieve this with superior thermodynamic conditions (i.e., high operating pressure and temperature), by significantly reducing the containment volume, and by eliminating the need for recirculation and jet pumps, pressurizer, steam generators, steam separators, and dryers.

Demonstration of a Supercritical Water-Cooled Reactor (SCWR) viability requires reliable assessment of reactor system stability and safety for which capability of accurate prediction of heat transfer and pressure losses in SCWR core geometries under typical supercritical fluid condition are needed. Considerable information exists about heat transfer to supercritical water in round tubes used in fossil boilers but little is known about the processes in geometries foreseen for SCWR cores.

In order to obtain realistic data for heat transfer in typical SCWR geometries a cooperative GIF test program using the supercritical water Benson Loop at Framatome ANP in Erlangen Germany is planned. In the framework of this international collaboration, INL will design and fabricate a test section which will be installed in the loop and a test campaign sponsored by the other participants will be conducted in 2007. The European partners will be responsible for adapting the loop, conducting the tests and collecting the required data. Also, the Benson loop testing is a part of agreements previously reached by US DOE for INERI's with Korea and Canada. The Korean partners will design and build a supercritical CO_2 loop with a test section similar to the section to be designed for the Benson Loop. The data obtained from the Korean loop and the data from the Benson loop will allow for development of scaling relations, which if satisfactory in turn would allow for using supercritical CO_2 in further thermal-hydraulic testing thus reducing costs of experimental program and increasing testing flexibility.

Section 2. of this report briefly describes the SCWR concept and why it is important to obtain heat transfer data specifically for the reactor operating conditions. A description of the Benson SCW test section is given in Section 3. The main purpose of this report is to document the design details of the SCW heat transfer test section developed at the INL. These details with supporting thermal and stress calculations are presented in Section 4.

2. Supercritical Water Cooled Reactor

The SCWR is basically a Light Water Reactor (LWR) operating at higher pressure and temperatures, as shown in Figure 1. Operation above the critical pressure eliminates coolant boiling so that the coolant remains single-phase throughout the system. The variation of the thermo-physical properties of water over the typical SCWR operating temperature range is shown in Figure 2. Note that the property variation is rather dramatic, albeit continuous. Although at supercritical pressure the fluid is a single phase, the fluid resembles a "liquid" at lower temperatures (core inlet), and a "vapor" at higher temperatures (core outlet) with an intermediate transition region.

Existing thermal-hydraulic correlations, models and codes, commonly used for safety analysis of LWR systems, are not validated for water at supercritical conditions. Simulation of nuclear reactors cooled by supercritical water is made inherently more complicated by the large variation of the thermodynamic and transport properties over the pressure and temperature range of interest. Supercritical-water thermal-hydraulics is also fundamentally different from two-phase flow thermal-hydraulics due to lack of interfaces with surface tension and because the variation of the properties is continuous, albeit large, for a supercritical fluid, while discontinuous for a two-phase fluid. For these reasons, the heat transfer, critical flow and other correlations and models used by the LWR codes are not generally applicable to supercritical conditions.

The incorporation of a SCW heat transfer test section into the existing Benson loop provides for an economical and versatile experimental facility capable of providing and analyzing required measurements for realistic geometries over the ranges of design and accident conditions possible in an SCWR prototype.

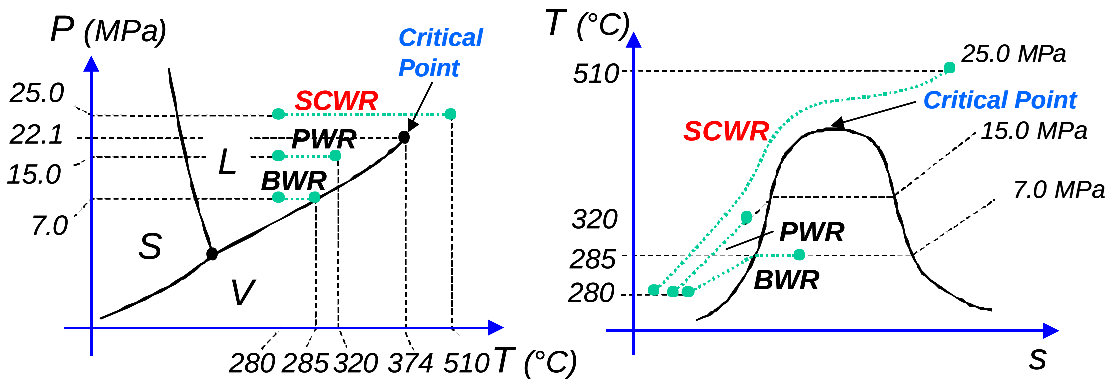


Figure 1. Pressure-temperature and temperature-entropy diagrams for water with the typical operating conditions of the SCWR, BWR, and PWR.

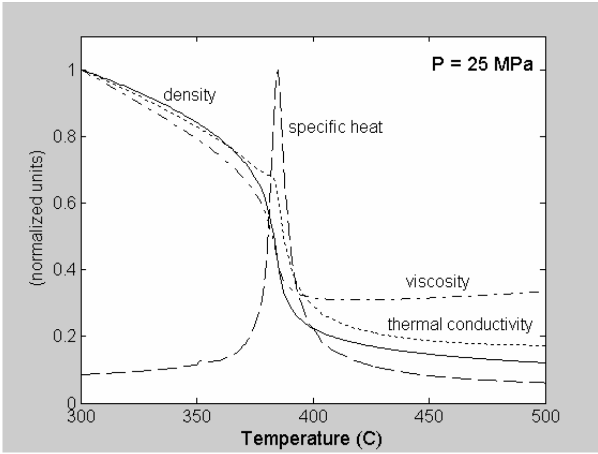


Figure 2. Variation of the thermo-physical properties of water at constant (supercritical) pressure.

3. The Benson Loop

The BENSON test rig[1] is a high-pressure test facility which is installed in an accredited laboratory at Framatome ANP in Erlangen, Germany and is unique throughout the world due to its wide range of operating conditions. As the name of the test rig implies, its main purpose is to investigate topics associated with the operation and further development of BENSON boilers which operate at supercritical water conditions. In addition to this, the test facility is also used for issues related to power generation using nuclear and renewable energy sources. The BENSON test rig, in operation since 1975, has been used for investigating numerous topics and has been continually adapted to new developments in science and technology. Its range of operating conditions is based on the service requirements of BENSON boilers and raw-gas heat-recovery steam generators. The test rig's design conditions are:

System pressure	330 bar
Temperature	600 °C
Mass flow	28 kg/s
Heating capacity	2000 kW.

As shown in Figure 3, the test facility mainly comprises a water supply system, the object to be tested, a pressurizer and a cooling system. In the water supply system, demineralized and deaerated water or boiler feedwater, to which chemicals have been added to obtain the required water chemistry, is provided in a feedwater tank. This water is injected into the test loop by a piston pump. To minimize flow oscillations caused by the pump's six pistons, a damping vessel is installed in the pump discharge line.

The water is heated in a main heater to establish the thermodynamic flow conditions required at the inlet to the test object. This coil-type heater is designed for direct electric heating; i.e. electric current flows through the wall of the coil which acts as a resistor and is thereby heated. The advantage of this heating method is that it allows precise control of the heat added to the fluid. This is particularly important in connection with the development of heat transfer and pressure drop correlations. Experiments using other methods such as radiation heating (performed directly in a power plant) are less suitable for such tasks since precise determination of fluid enthalpy or of actual heat input is more difficult.

After the fluid has passed through the main heater it enters the test section, where the flow and heat transfer conditions are simulated and monitored. The test object can consist of various kinds of tubes or rod bundles or vessels which can be oriented in either the vertical or horizontal position.

Installed downstream of the test object is a spray-type condenser for condensing the steam fraction and subcooling the fluid. The subcooled fluid then passes to a circulation pump which recirculates part of the flow for cooling the spray condenser. Condenser cooling water is taken from the main flow immediately downstream of the pump as well as from the main cooler which is supplied on its secondary side with water from a wet cooling tower (trickle cooler).

System pressure is controlled by a large thermal pressurizer and a throttling valve (pressure-reducing valve) downstream of the test object. Assurance of a constant pressure is particularly important for investigations performed near the critical pressure since pressure fluctuations can affect heat transfer conditions in the test object.

If the mass flow exiting the test loop is smaller than that supplied by the piston pump, the level of water inside the pressurizer initially rises. This does not, however, lead to any increase in system pressure since the steam cushion provided inside the pressurizer is compressible. The rise in water level is, however, used as a process control variable to open the pressure-reducing valve at the end of the test loop.

If large mass flows are required for certain investigations, the test rig can be operated in the recirculation mode. In this case the water is not injected into the test loop by the piston pump, as when the test rig is operating in the once-through mode, but is recirculated by the circulation pump instead.

The entire test facility is made of austenitic stainless steel and is thermally insulated by means of an approximately 50-mm-thick layer of rockwool. The test rig and the test object are instrumented in such a way that all relevant parameters such as temperature, pressure and flow can be measured.

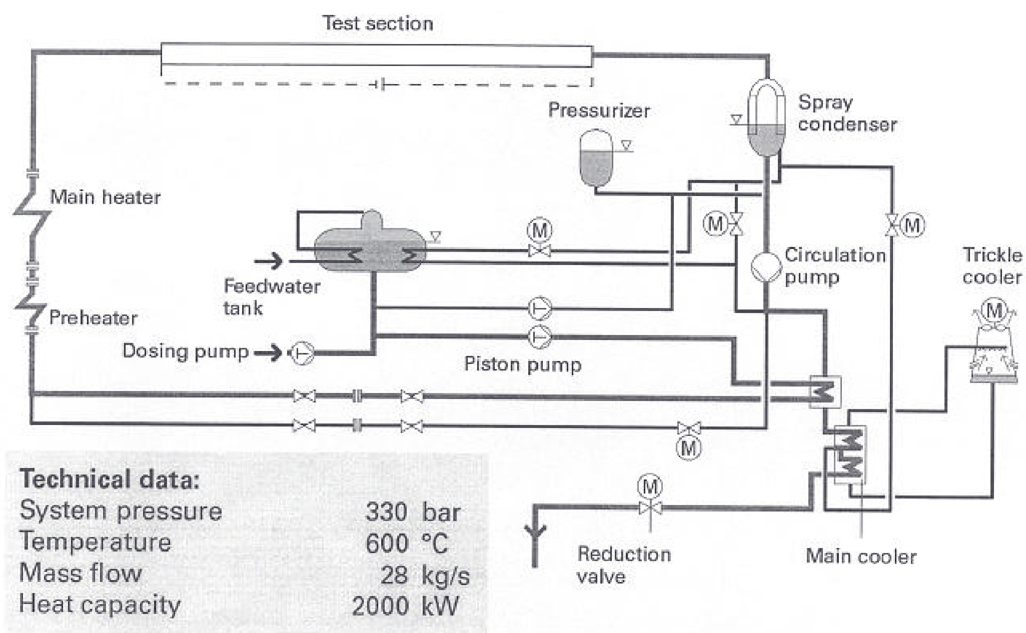


Figure 3. Flow diagram of BENSON test rig

4. Heat Transfer Test Section

4.1 Heat Transfer Test Section Requirements

In December 2004 a meeting was held at Framatome ANP in Erlangen, Germany to identify requirements for the heat transfer test section. The meeting was attended by experts from Framatome, Forschungszentrum Karlsruhe, the Korean Atomic Energy Research Institute (KAERI), and the INL. Thermal-hydraulic phenomena expected in the SCWR core were discussed and a concept for the test section was identified.

Several SCWR concepts are being considered by the GIF partners. Therefore the test section needs to be designed so that usable data for all partners can be generated. Some of the proposed SCWR designs include cold coolant flowing downwards within moderator channels in the core. Heat transfer to these moderator channels will affect the bulk core coolant temperature and therefore the heat transfer from the fuel pins and the fuel pin cladding temperature. There is also a concept with solid moderator rods and a concept without moderator channels or rods in the flow channel. The test section design is such that all of these concepts can be accommodated with relatively simple modifications to the test section.

Since there is not yet an optimized design of a SCWR, the rod diameter was chosen to represent a potential range of fuel pin diameters. The diameter of a fuel pin (and therefore of the heater rod) is also a limiting factor for the number of thermocouples that can be placed in a rod. A typical length of a full length fuel rod is about three meters. The few thermocouples that could be placed in a rod of this length would not provide adequate resolution on heat transfer phenomena over the full length. Therefore a shorter test section was decided upon which gives more thermocouples per unit length of heater rod. This short test section would simulate any portion of the actual heater rod by controlling the inlet temperature of the coolant. The sliding "enthalpy window" concept will provide sequential simulation of the thermal-hydraulic conditions along the length of the SCWR core and provide for a concentration of thermocouples in the region of interest.

The heat transfer test section will be instrumented sufficiently to determine heat transfer coefficients at selected positions along the heater rods. Thermocouples will be used to monitor the heater rod surface temperature, the core barrel wall temperature and the core coolant temperatures. Taps are provided to measure pressure drop along the bundle length. Core coolant and moderator flowrates will also be measured.

Based on the above general requirements a set of design specific requirements was developed with GIF partners for the test section and instrumentation and is shown in Table 1 and Table 2 respectively.

Table 1: SCWR Heat Transfer Test Section Requirements

Bundle geometry	2x2, square tube insert
Maximum Pressure	25 MPa = 3625 psia
Test section water inlet temperature (enthalpy window) both for coolant and moderator (individually chosen); two independent moderator flows	280 to 488°C
Maximum test section water outlet temperature	550°C
Maximum test section power flux	1500 kW/m^2
Heater rod diameter	10 mm or equivalent
Heater rod heated length	1 m
Inlet length (unheated)	0.5m
Outlet length (unheated)	0.5m
Number of spacer grids	3 (at least)
Range of Coolant Mass flux	200 – 1000 kg/(m2s)
Number of heater rods	4 (one replaceable dummy rod (square))
Rod spacing to diameter ratio (pitch)	1.15
Direct or indirect heated rods	Indirect

Table 2. SCWR Heat Transfer Test Section Required Instrumentation

Instrumentation:	
Inlet- and outlet conditions: Static pressure, temperature, mass flow rate	
Static pressure: 5 pressure drop measurements after 2^{nd} spacer, 1 before 2^{nd} spacer	(distance in the order of 10 cm or closer)
Temperatures of the cladding and the box walls. Bulk temperature. 8 thermocouples per rod. (8 of 32 reserved for positions just underneath the spacers for safety reasons)	

Figure 4. shows a flow and instrumentation schematic of the proposed heat transfer test section. Also shown are the interfaces between the test section and the Benson SCW Loop.

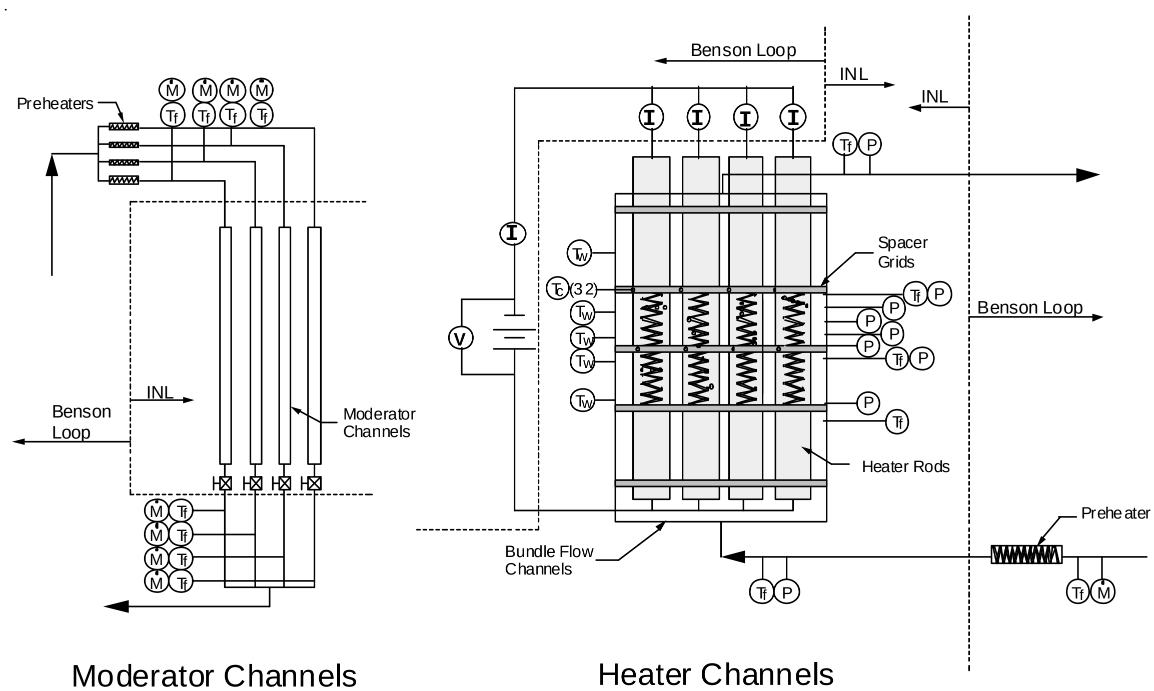


Figure 4. Flow and Instrumentation schematic for SCW heat transfer test section.

4.2 Test Section Design Details

An overview of the heat transfer test section is shown in Figure 5. The main coolant from the Benson loop enters the test section from the bottom and flows upward through the core simulator and out near the top, then back to the Benson loop. The flowrate, temperature, and pressure are controlled in the Benson loop as shown in Figure 4. The moderator flow also from the Benson loop enters the test section near the top of the vessel in four individual inlet pipes, one for each of the moderator channels. The moderator flow is downward through the four channels and exits the test section below the heated region of the core. The inlet temperature and flowrate for each of the moderator channels are controlled individually in the Benson loop as also shown in Figure 4.

Power to the heater rods comes from the Benson loop power supplies. Power control is also provided by the Benson loop. Output from all of the instrumentation installed in the heat transfer test section is recorded on the Benson loop data acquisition system.

The design philosophy for the heat transfer test section was to, as much as possible, use available off the shelf components such as standard size pipe, pipe fittings, flanges, seals etc. in order to avoid the specialized fabrication of individual components.

The following subsections describe the individual components of the heat transfer test section in detail.

Pressure Boundary

The pressure boundary is primarily fabricated from a nominal 2-1/2 in. diameter XXH stainless steel pipe which has an inside diameter of 1.771" (4.5 cm) and an outside diameter of 2.865" (7.28 cm). (See Figure 5.) An 2500 lb ANSI B16.5 raised face flange is welded to the top of the pipe. The core barrel, which defines the core flow channel and the four moderator channels, hangs from this upper flange. A 2-1/2" x 1-1/2" pipe cross is welded to the upper mating flange which provides access for the heater rod upper power leads, the core barrel wall thermocouples, and the core outlet flow. A Grayloc® butt weld hub is welded to the bottom of the pipe. A 2-1/2" x 2-1/2" Grayloc® cross is attached to the lower Grayloc® hub and provides access for the core inlet flow and the lower heater rod power leads. The total length of the pipe section including the flange and hub is 88.3" (224.28 cm).

Connections to the test section are made using Grayloc® flanges similar to that shown in Figure 6.

A Grayloc® connector has three components: a metal seal ring, two hubs and a clamp assembly. The seal ring is a "T" in cross section. The leg of the "T" forms a rib that is held by the hub faces as the connection is made. The two arms form lip seals that create an area of sealing surface with the inner surface of the hub. The clamp fits over the two hubs and forces them against the seal ring rib.

As the hubs are drawn together by the clamp assembly, the seal ring lips deflect against the inner sealing surfaces of the hubs. This deflection elastically loads the lips of the seal ring against the inner sealing surface of the hub, forming a self-energized seal. Internal pressure reinforces this seal, so that the sealing action of the connector is both self-energized and pressure-energized.

The Grayloc® hubs are manufactured to fit most standard pipe sizes, as nipples that can be machined to provide a weld fitup to most any surface, and as blind hubs which can be drilled or machined to accommodate various penetrations or connections.

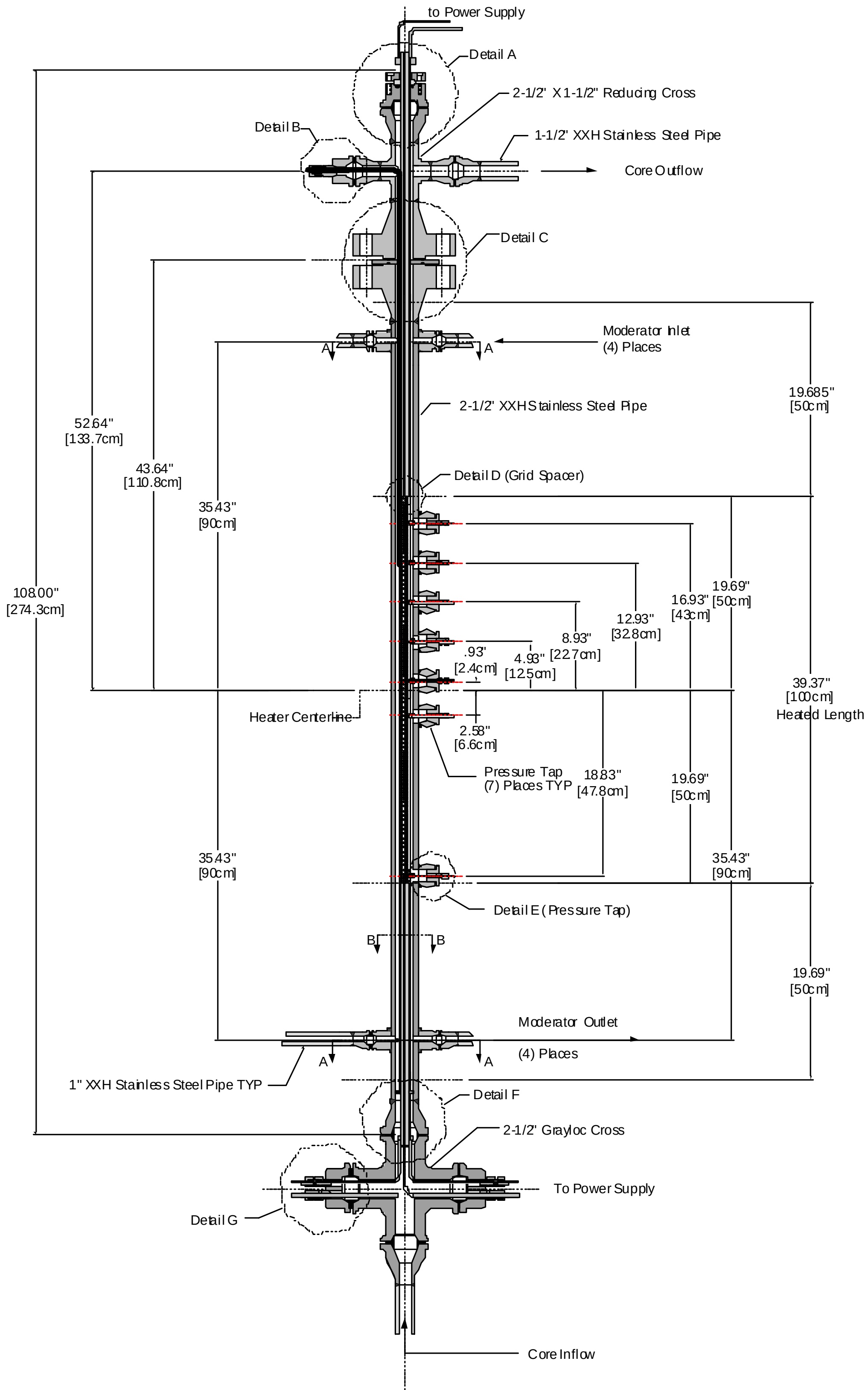


Figure 5. Supercritical water heat transfer test section layout.

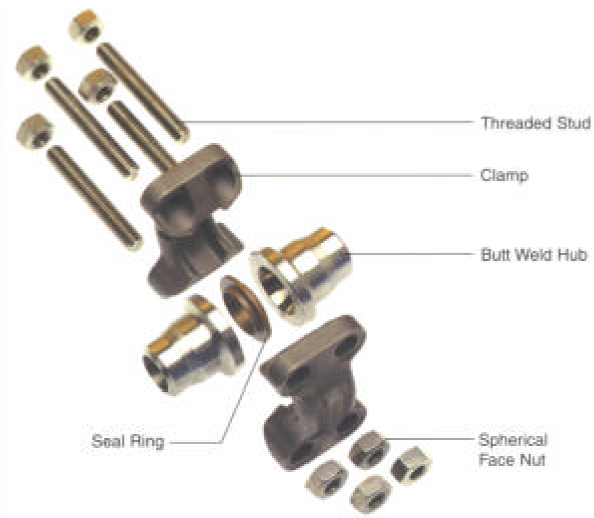


Figure 6. Grayloc® flange assembly.

A stress analysis of the pressure boundary components is in progress by INL personnel. Initial recommendations are that a higher strength stainless steel material such as SA-312 TP316N will be needed. The preliminary analysis is included in this report as Appendix A.

Core Barrel

The core barrel fits inside the main pressure boundary pipe and defines the channels for the core flow and the four moderator flows. The core barrel assembly is shown in Figure 7, with the cross section FF shown in figure 8. The small holes near the center of the flange are for the passage of the core fluid and core barrel surface temperature thermocouples.

The core barrel flange is welded to the top of the straight section of the core barrel. The entire assembly is supported by the flange on the upper end of the main pressure boundary as shown in Figure 9.

Two Garlock Helicoflex® seals are used to seal the core barrel flange between the two raised face flanges which form the pressure boundary. The sealing principle for the Helicoflex® seal, shown in Figure 10, is based on the plastic deformation of a jacket of greater ductility than the flange material. This occurs between the sealing face of a flange and an elastic core composed of a close wound helical spring. The spring is selected to have a specific compression resistance. During compression, the resulting specific pressure forces the jacket to yield and fill the flange imperfections while ensuring positive contact with the flange sealing faces, Each coil of the helical spring act independently and allows the seal to conform to surface irregularities on the flange surface.

The seal between the corners of the core barrel and at the bottom of the core barrel, and the pressure boundary pipe is composed of strands of braided flexible GRAPH-LOCK® graphite contained by an inconel filament jacket. The inconel wire filament has a diameter of .004”.

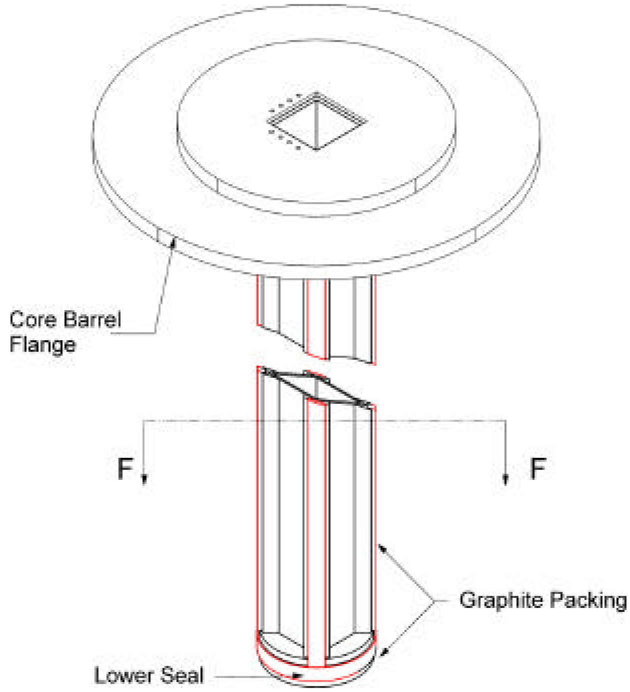


Figure 7. Core barrel assembly

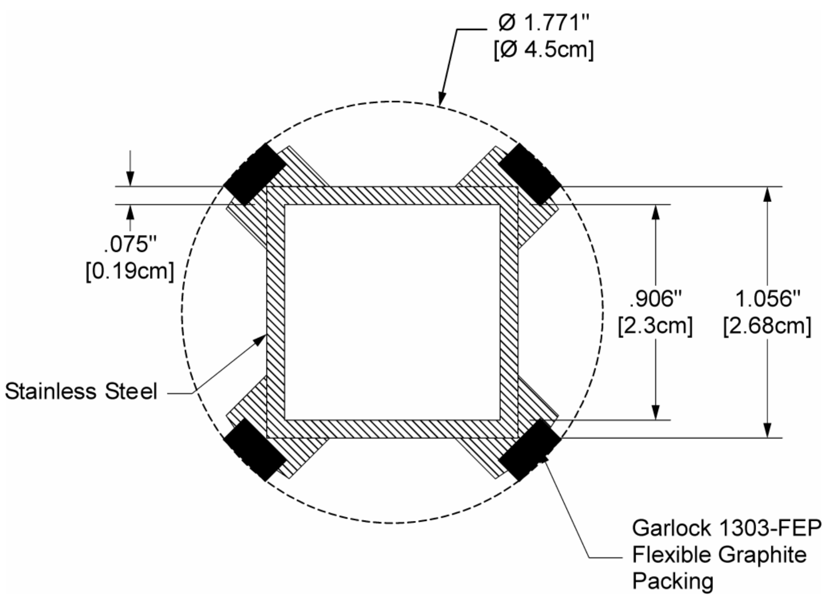


Figure 8. Core barrel SECTION F-F.

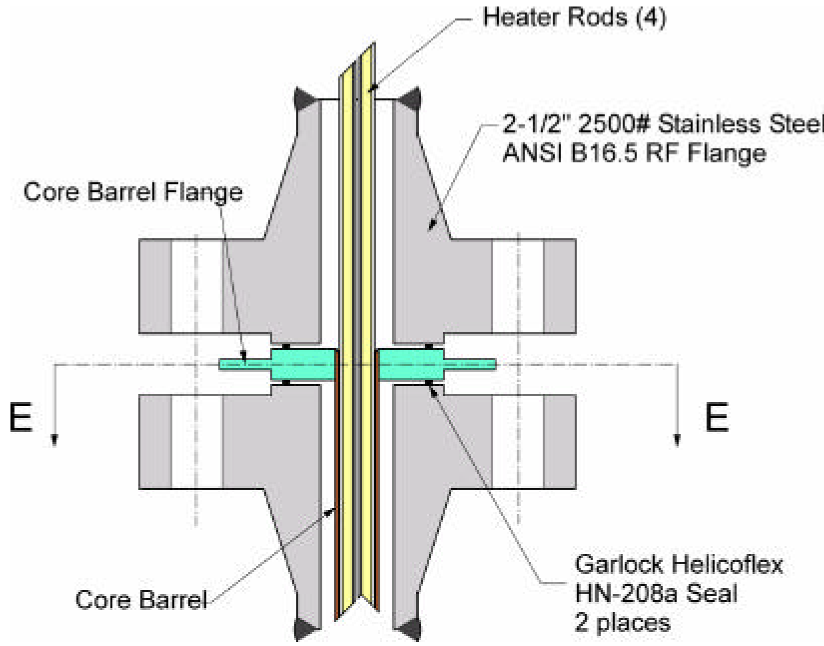


Figure 9. Core Barrel shown sealed between pressure boundary flanges.

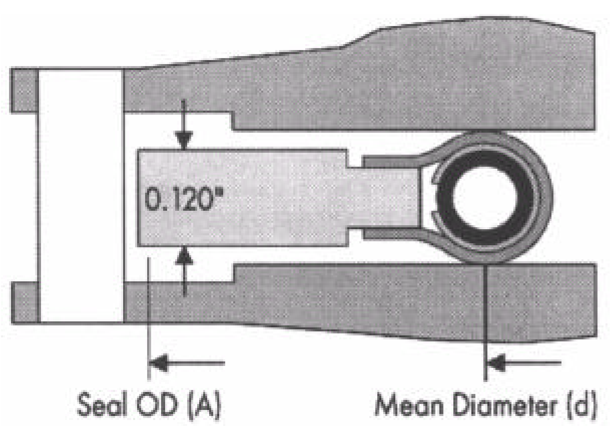


Figure 10. Illustration of Garlock Helicoflex® seal.

To get a better perspective of the relationship to the various test section internals, Figure 11 is presented which shows a section view of the test section just below the heated portion of the core.

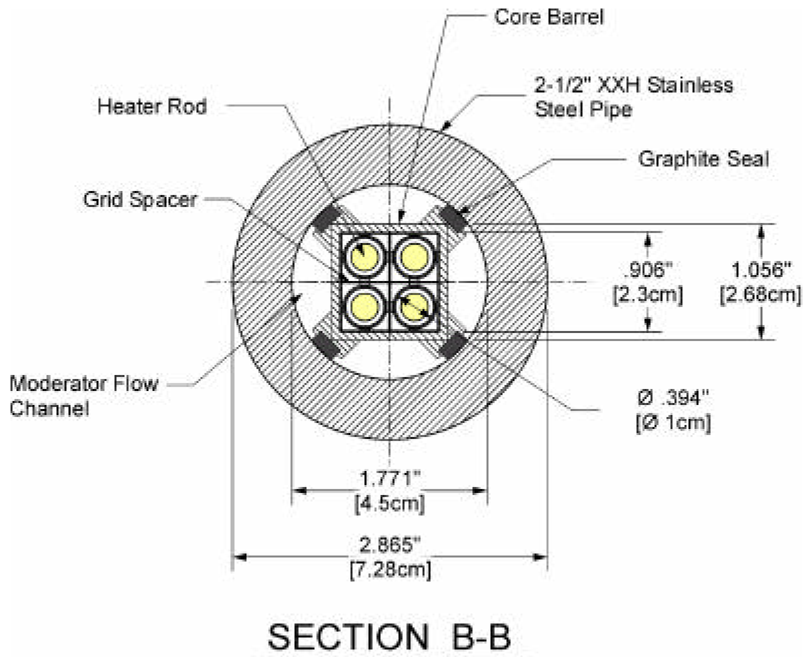


Figure 11. Cross section of initial test section design.

Given that the heater rods are 1.0cm. in diameter with a pitch to diameter ration of 1.15, the inside side length of the core barrel was determined such that each heater rod was centered in its quarter quadrant of the core barrel. This gave the inside dimensions of the core barrel as 0.906" x 0.906" (2.3cm. x 2.3cm.) as shown in Figure 11. At the Erlangen design review held in March, 2005, some concern was raised that using the above criteria for sizing the core barrel side dimension may not necessarily provide uniform cooling around the circumference of the heater rod and could lead to unacceptable differences in the rod wall temperature from one side of the rod to another. The participants from Forschungszentrum Karlsruhe accepted the assignment to investigate this concern by performing a thermal analysis of the test section.

A parametric study was performed by C. Waata[2], FZK using the sub-channel analysis code STAFAS. For all cases of this study, three different inner wall lengths of 2.3, 2.4 and 2.5cm have been investigated. All other geometric parameters have been set constant. Boundary conditions assumed are: adiabatic from the moderator channel to the pressure tube; inlet conditions of the moderator water set equal to the inlet temperature of the coolant. Heat transfer is considered from the cladding to the coolant, coolant to box walls, and box walls to moderator channel. The moderator mass flow has been set constant to 20% of the total mass flow for all calculations. The modelling notation for the STAFAS code is shown in Figure 12.

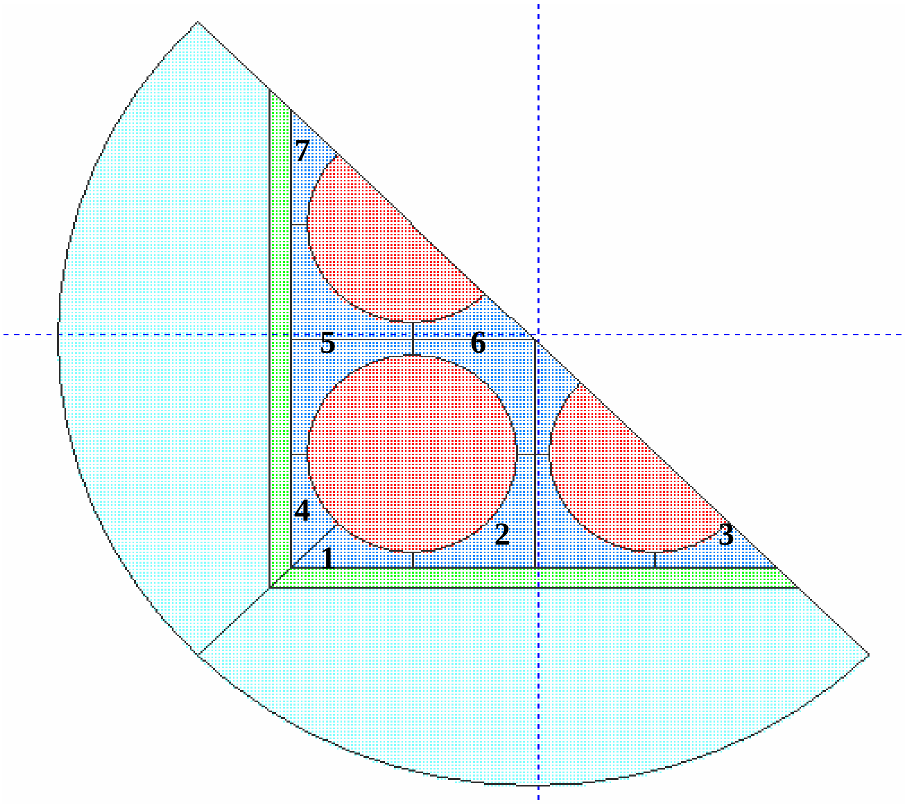


Figure 12. Subchannel notation for the STAFAS model of heat transfer test section.

A total number of six case studies have been carried out as shown in Table 3. A reference case was selected defining a mean heat flux of 1000 kW/m^2, a mass flux of 1000 kg/m^{2}s, and an inlet temperature of 350°C. For this reference case, the coolant and cladding temperatures as a function of axial position are shown in Figures 13 and 14 respectively.

Five were derived from the reference case. For cases A and B, the inlet temperature of 280°C and 450°C respectively was used. These results are shown in Figures 15 thru 18. Cases C and D were run at heat fluxes of 500 and 1500 kW/m^2 respectively. The results for Cases C and D are shown in Figures 19 thru 22. Case E was run at a reduced mass flux of 500 kg/m^{2}s. The results are shown in Figures 23 and 24.

Table 3, Case Matrix for STAFAS Analysis

Inner box length 2.3 cm

Case	Power Flux q'' (kW/m^2)	Mass Flux (kg/m^2s)	Inlet temperature (˚C)	Average exit temperature (˚C)
Ref	1000	1000	350	385.8
A	1000	1000	280	372.3
B	1000	1000	450	617.1
C	500	1000	350	378.8
D	1500	1000	350	394.9
E	1000	500	350	423.2

Inner box length 2.4 cm

Case	Power Flux q'' (kW/m^2)	Mass Flux (kg/m^2s)	Inlet temperature (˚C)	Average exit temperature (˚C)
Ref	1000	1000	350	384.0
A	1000	1000	280	361.1
B	1000	1000	450	581.4
C	500	1000	350	376.0
D	1500	1000	350	388.0
E	1000	500	350	400.4

Inner box length 2.5 cm

Case	Power Flux q'' (kW/m^2)	Mass Flux (kg/m^2s)	Inlet temperature (˚C)	Average exit temperature (˚C)
Ref	1000	1000	350	382.5
A	1000	1000	280	351.1
B	1000	1000	450	556.3
C	500	1000	350	373.3
D	1500	1000	350	386.1
E	1000	500	350	391.0

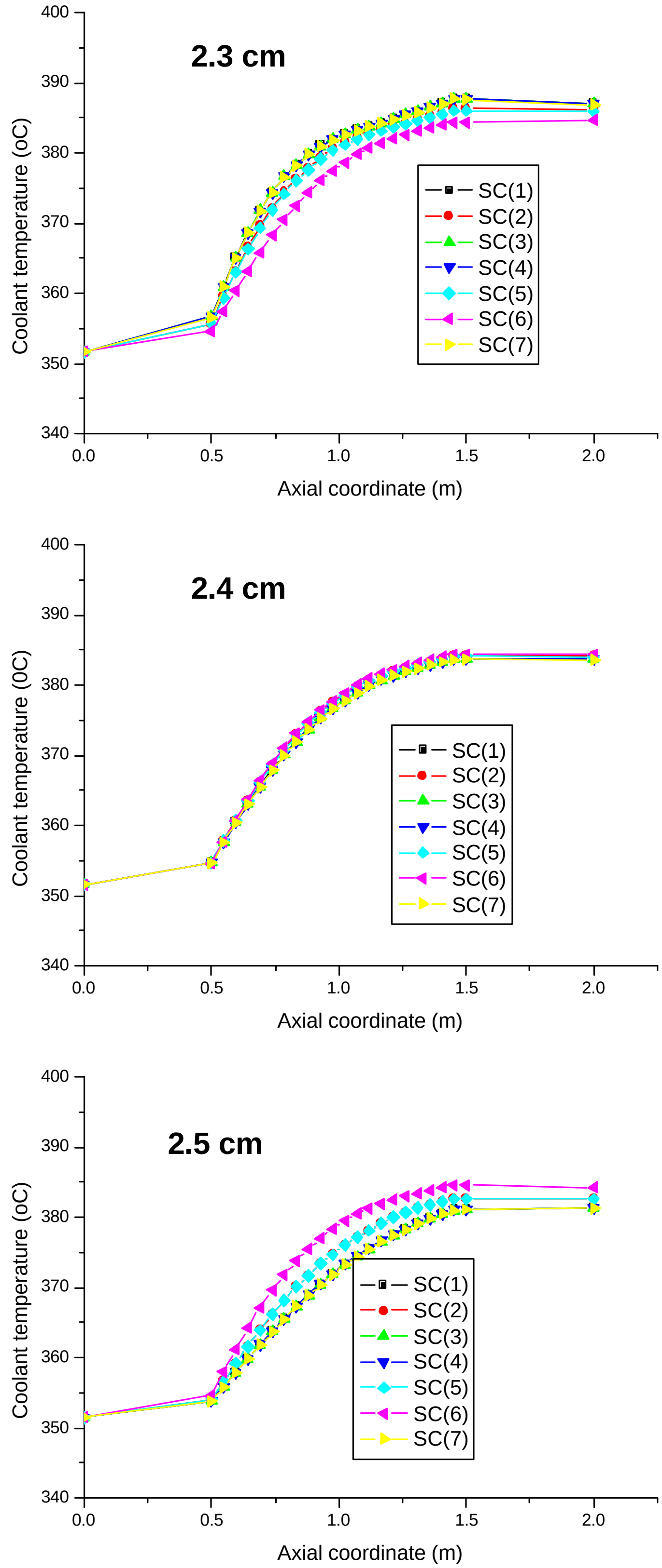


Figure 13. Coolant Temperature for **Reference Case**
q''=1000 kW/m^2, G=1000 kg/m^2s, Tinlet=350 $^{\circ}$C

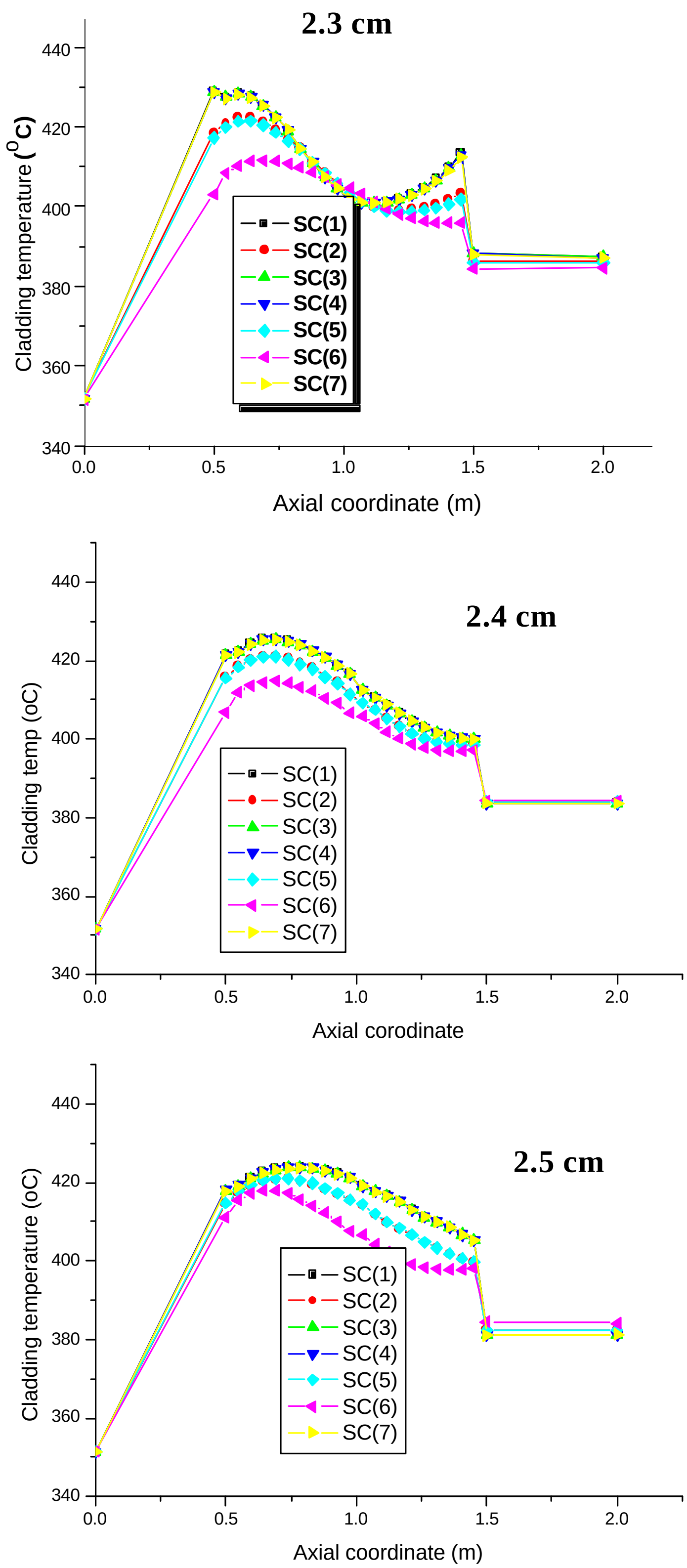


Figure 14. Cladding Temperature for **Reference Case**
q''=1000 kW/m^2, G=1000 kg/m^2s, Tinlet=350 $^{\circ}$C

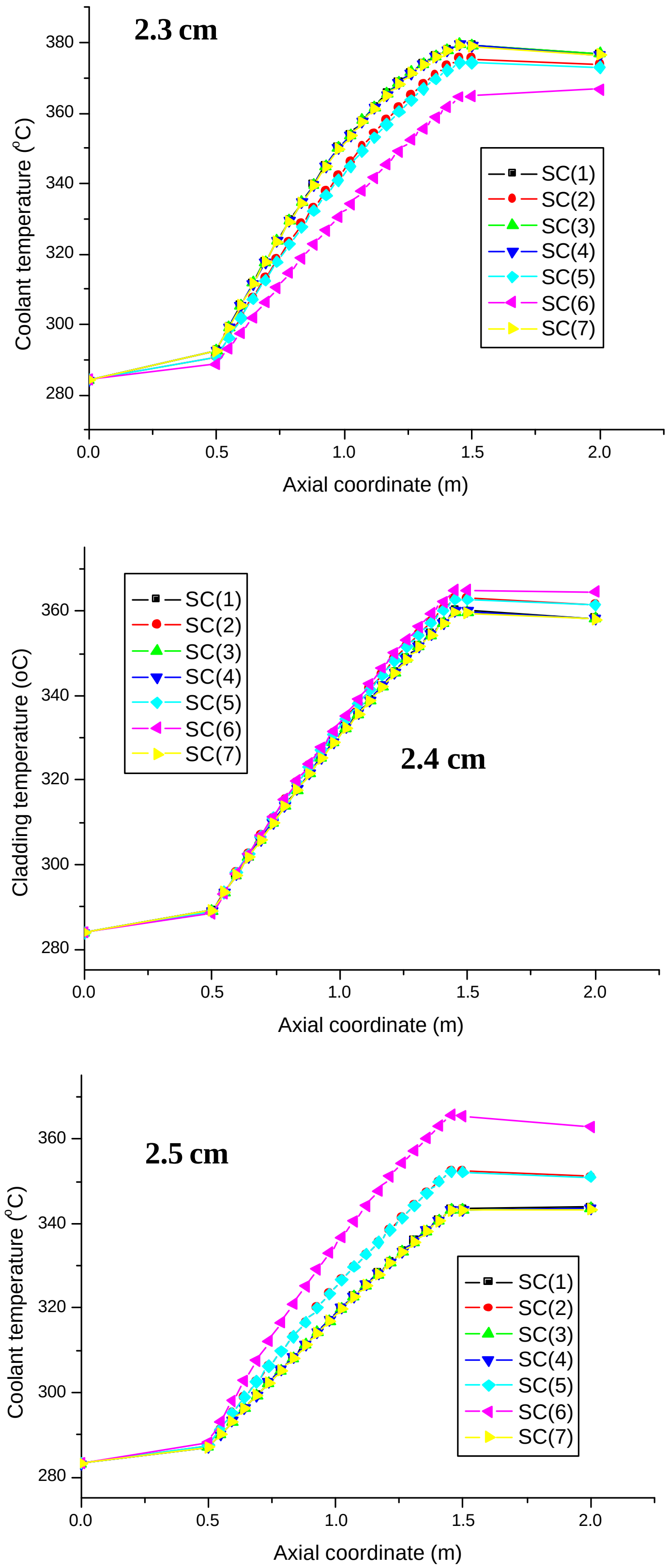
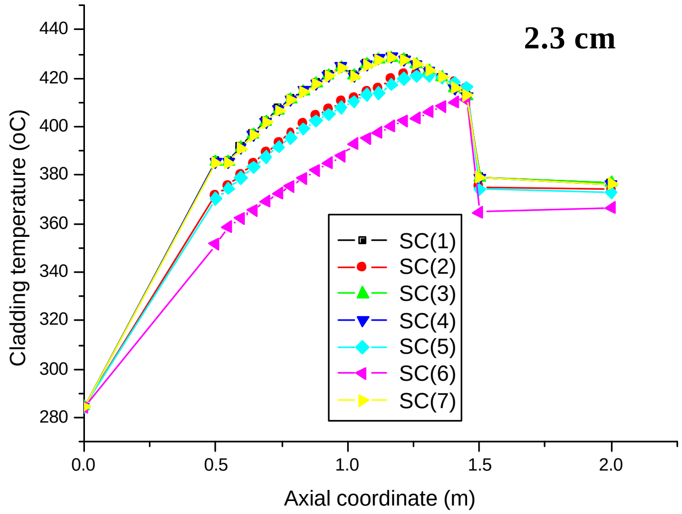
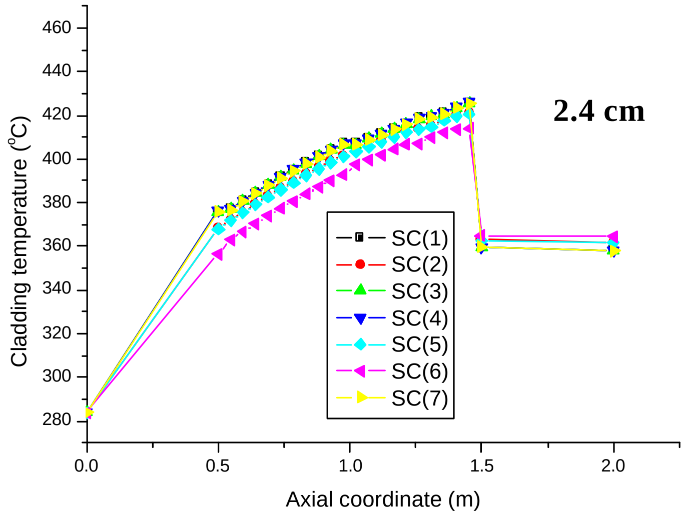


Figure 15. Coolant Temperature for **Case A**
q''=1000 kW/m^2, G=1000 kg/m^{2}s, Tinlet=280 $^{\circ}$C





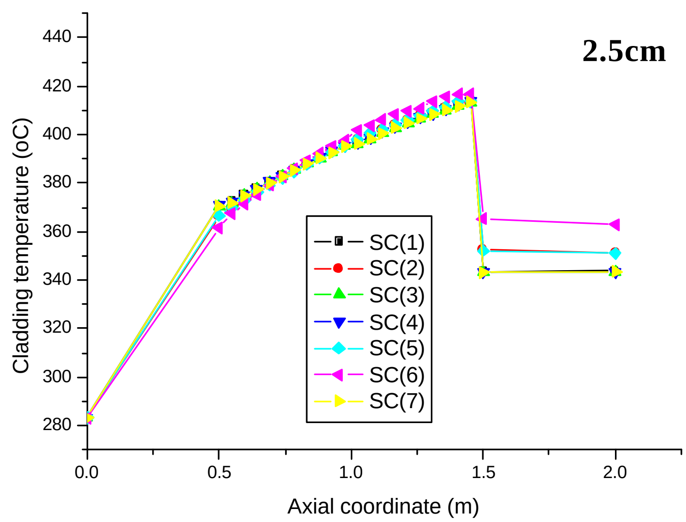


Figure 16. Cladding Temperature for **Case A**
q''=1000 kW/m^2, G=1000 kg/m^{2}s, Tinlet=280 $^\circ$C

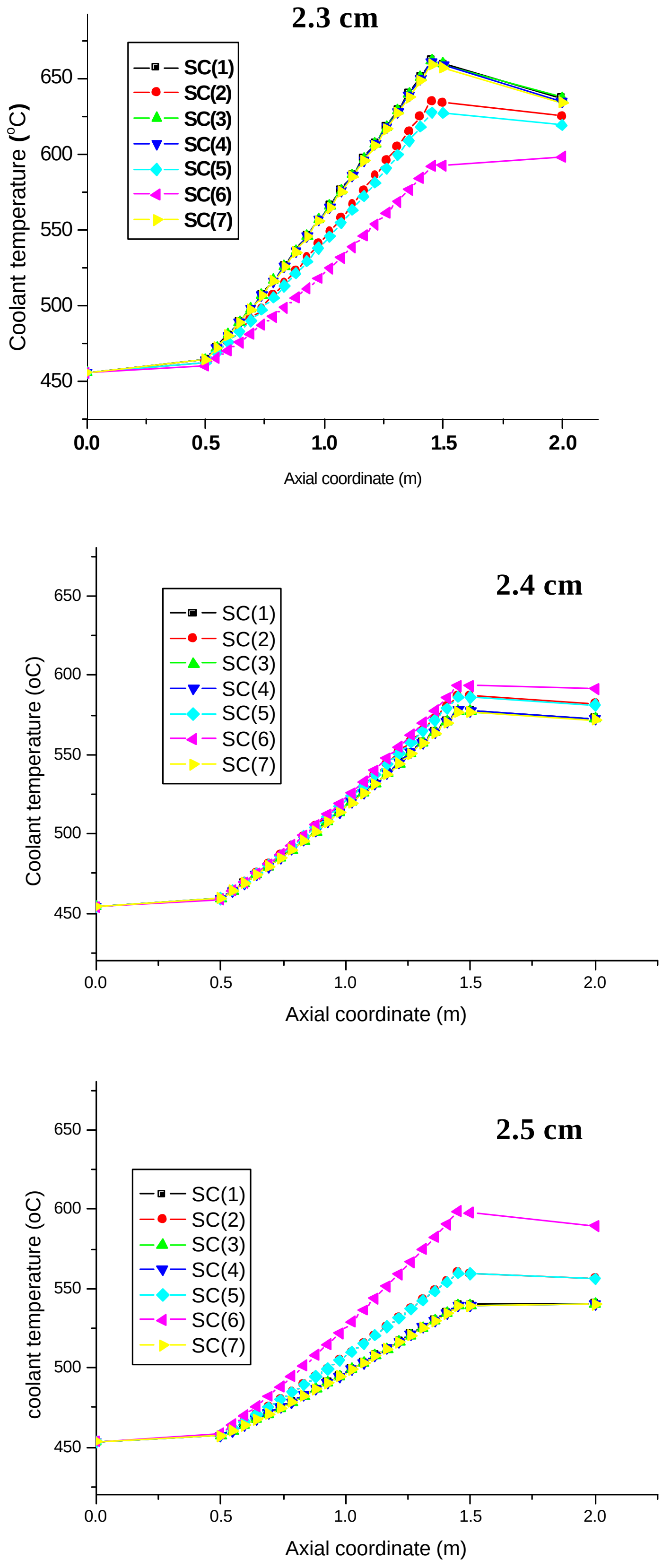


Figure 17. Coolant Temperature for **Case B**
$q''=1000\ kW/m^2$, $G=1000\ kg/m^2s$, Tinlet=450 °C

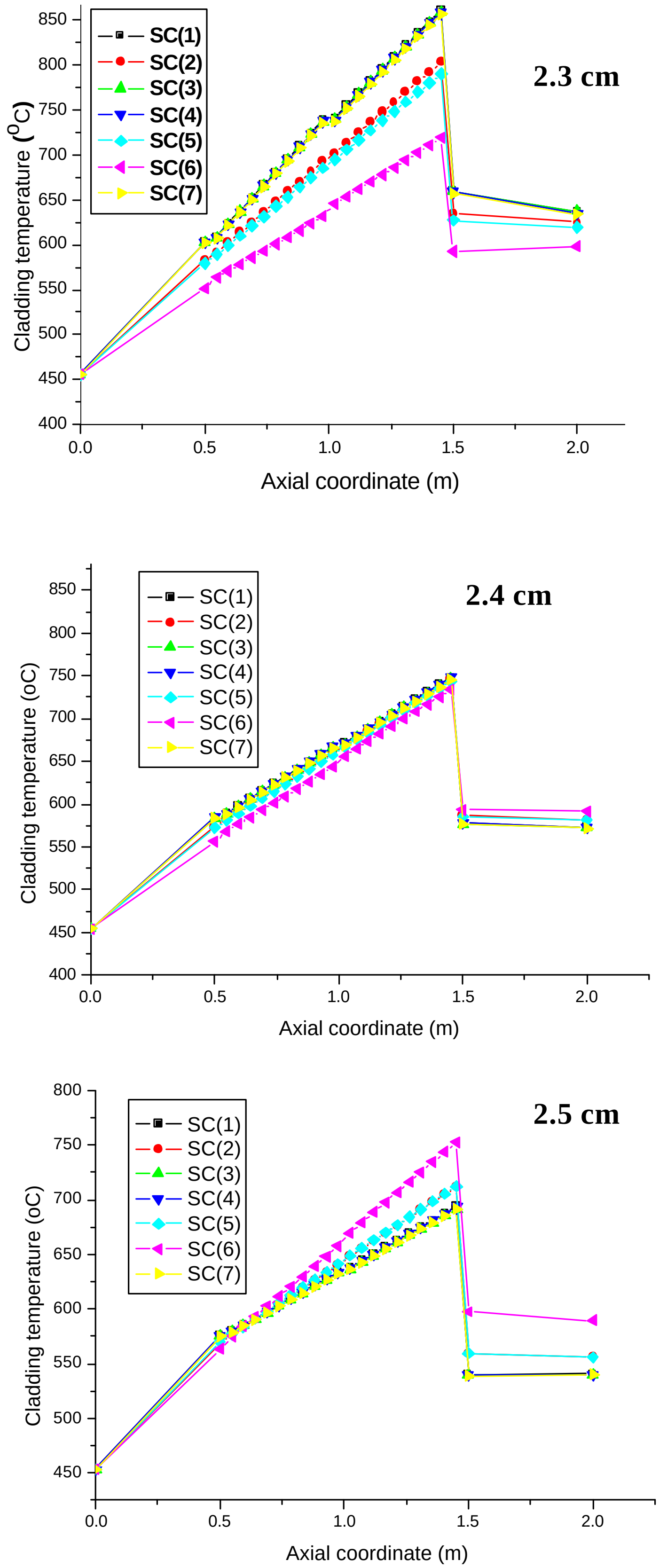


Figure 18. Cladding Temperature for **Case B**
$q''=1000\ kW/m^2$, $G=1000\ kg/m^2s$, Tinlet=450 °C

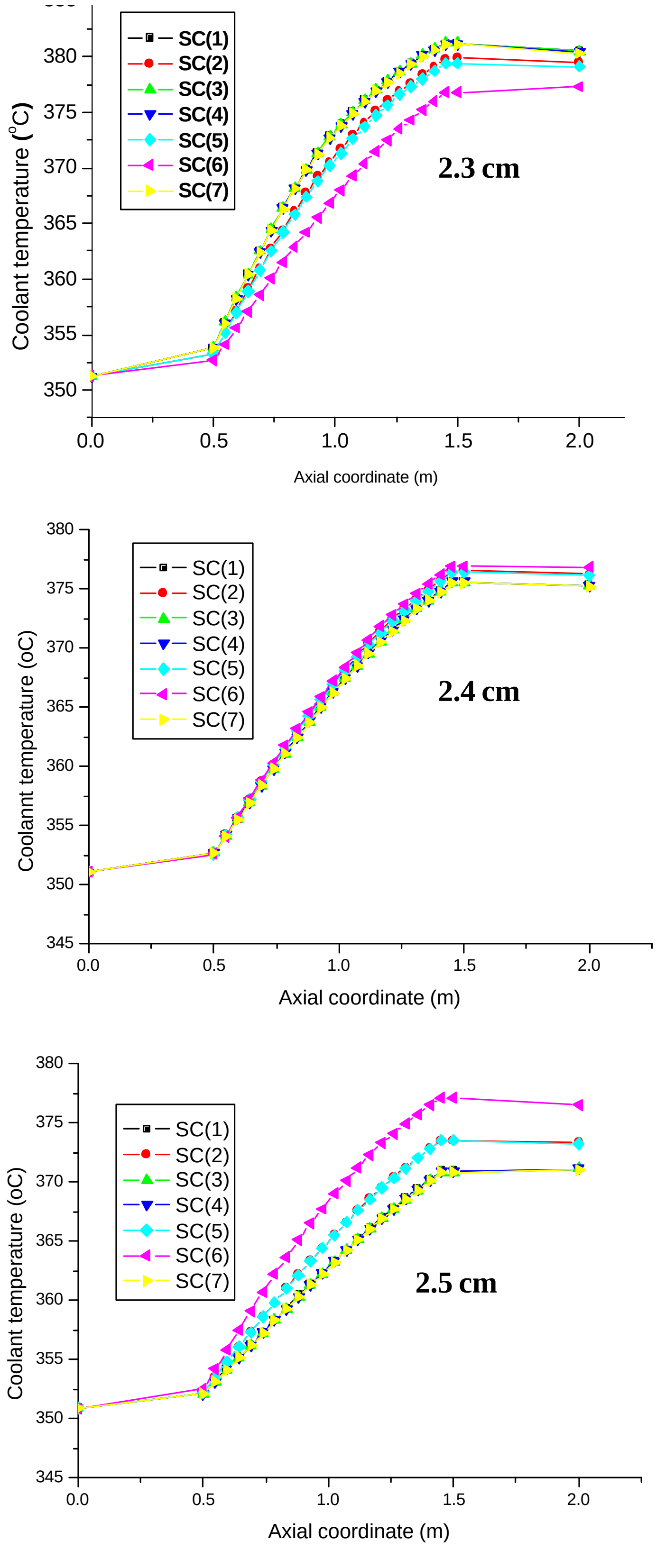
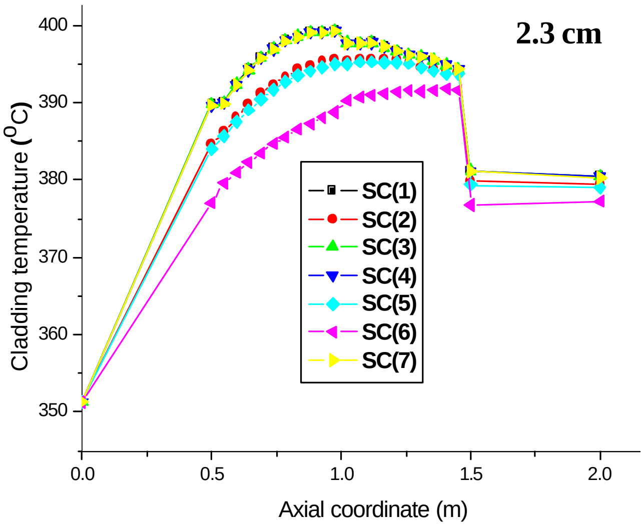
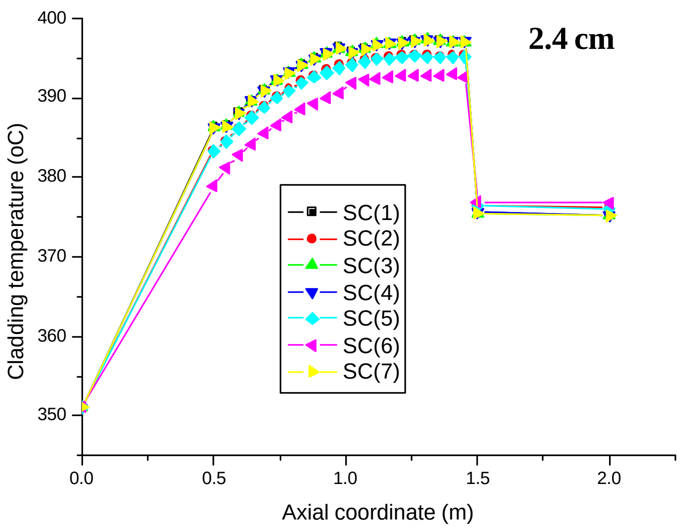


Figure 19. Coolant Temperature for **Case C**
q''=500 kW/m^2, G=1000 kg/m^{2}s, Tinlet=350 °C





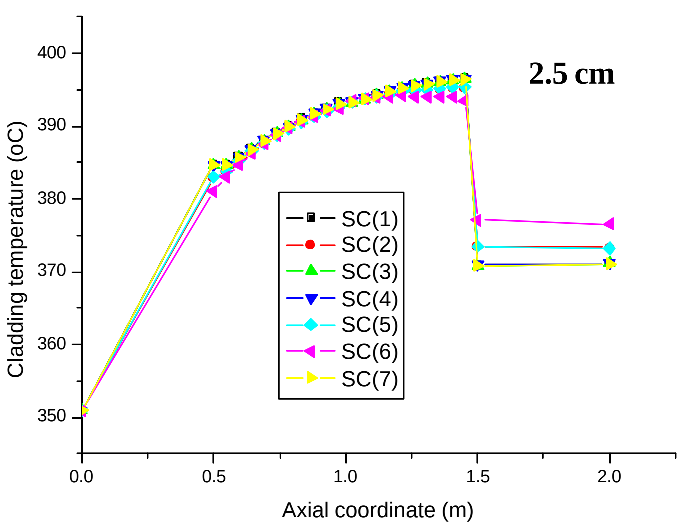


Figure 20. Cladding Temperature for **Case C**
$q''=500\ kW/m^2$, $G=1000\ kg/m^2s$, Tinlet=350 °C

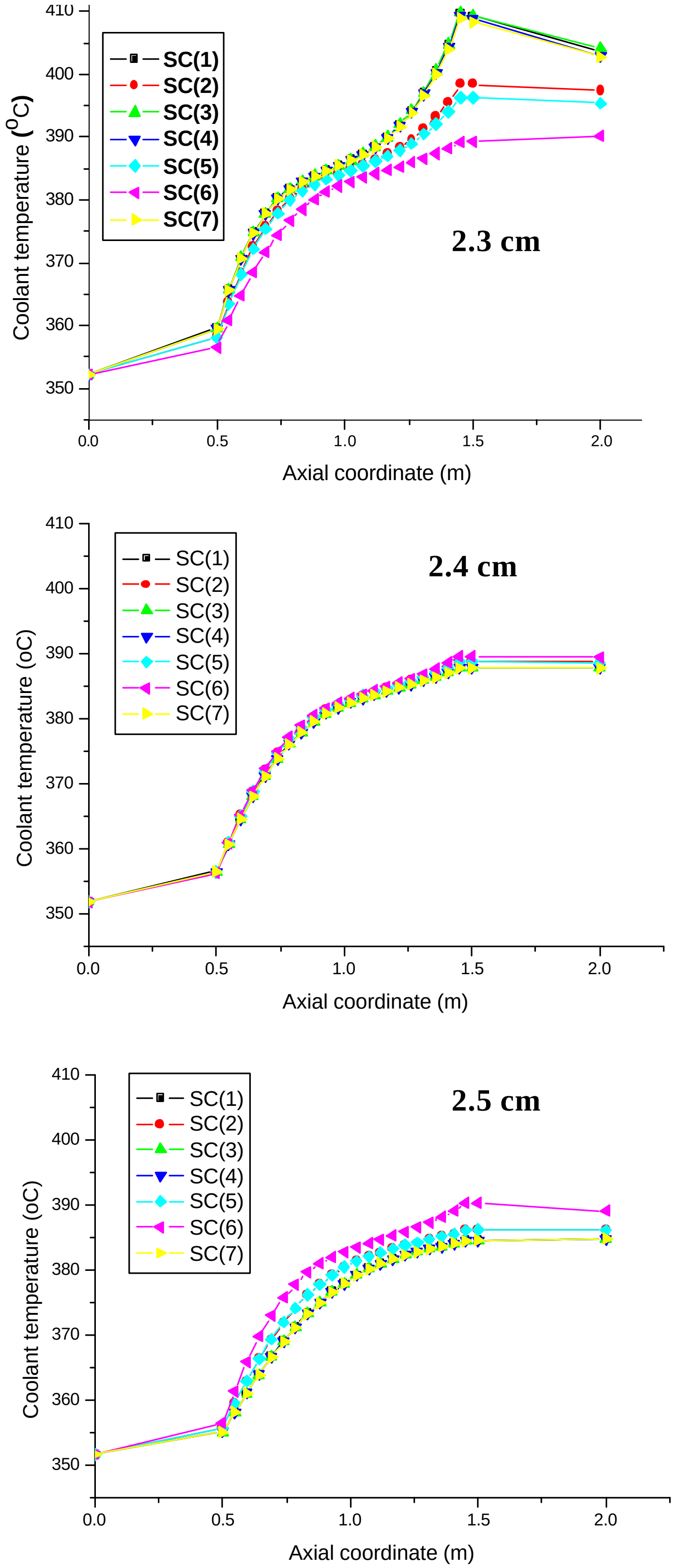


Figure 21. Coolant Temperature for **Case D**
q''=1500 kW/m^2, G=1000 kg/m^{2}s, Tinlet=350 $^{\circ}$C

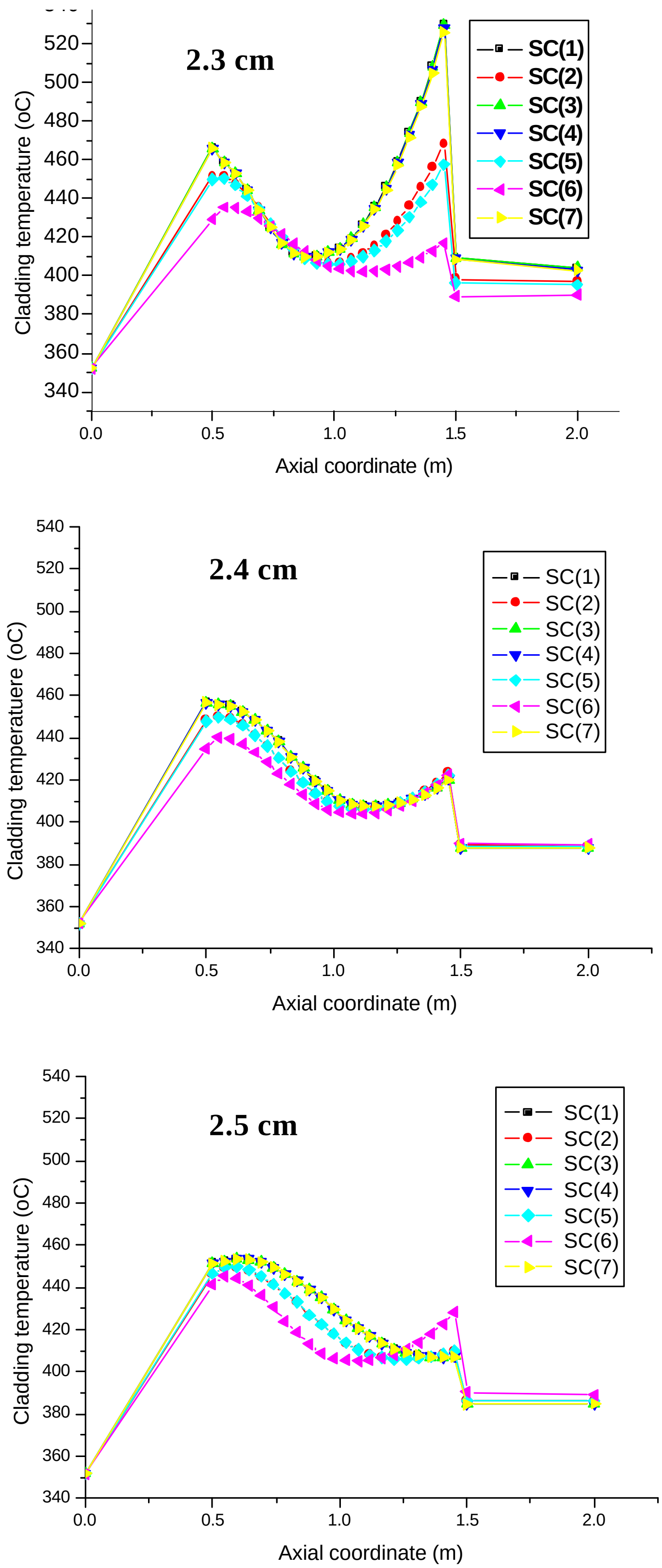


Figure 22. Cladding Temperature for **Case D**
q''=1500 kW/m^2, G=1000 kg/m^{2}s, Tinlet=350 $^{\circ}$C

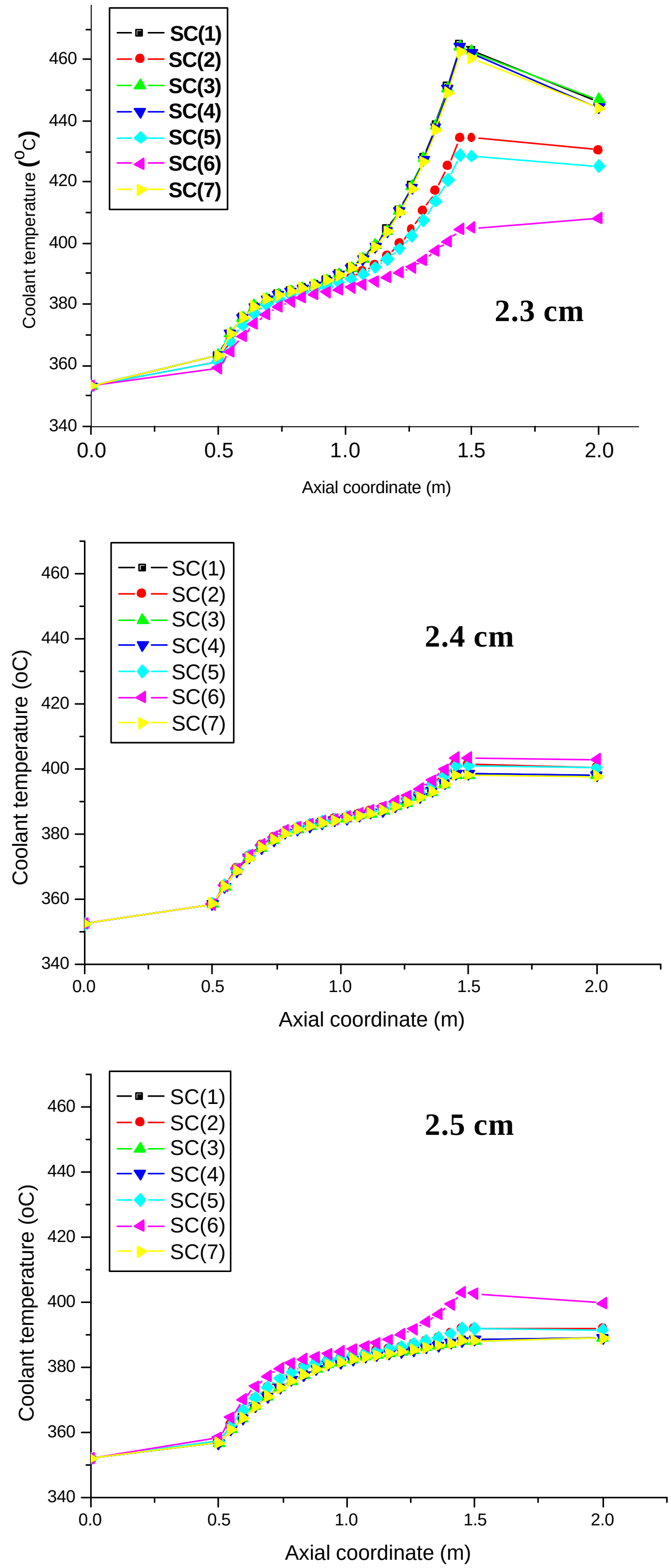


Figure 23. Coolant Temperature for **Case E**
q''=1000 kW/m^2, G=500 kg/m^{2}s, Tinlet=350 $^\circ$C

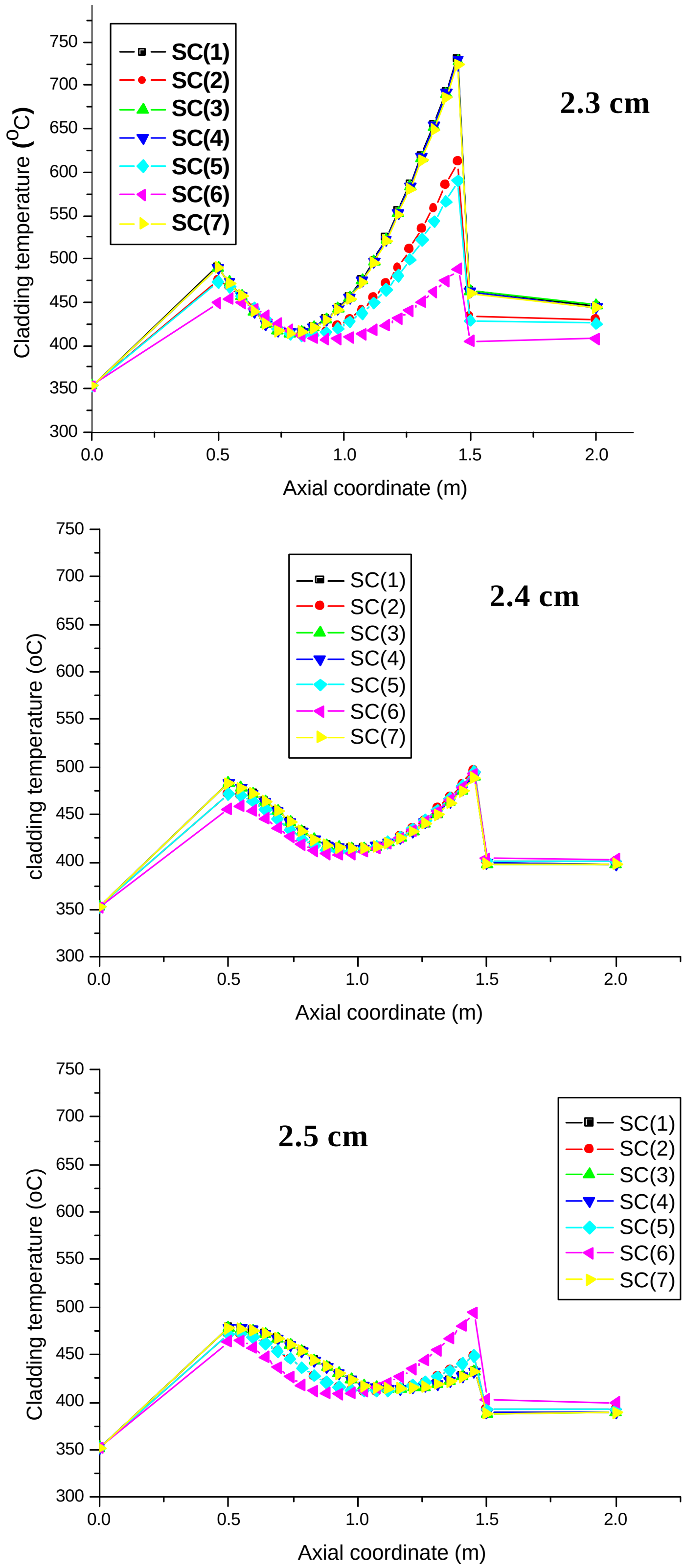


Figure 24. Cladding Temperature for **Case E**
q''=1000 kW/m^2, G=500 kg/m^{2}s, Tinlet=350 $^\circ$C

The comparison of the results for the three different inner side lengths of the box showed that the 2.4cm side length provides the best results for all six cases. “Best” means that the cladding temperature spreading for sub-channels reaches a minimum. Especially for the cases D and E the difference between maximum and minimum cladding temperature drops from more than 200°C to the order of 20°C (case E) and from more than 140°C to about 20°C (case D). For the 2.4cm box length, the maximum cladding temperature can be kept under 520°C (case E) instead of reaching almost 700°C. The coolant temperatures are much more homogeneous for 2.4cm than for 2.3 or 2.5cm.

Under low heat flux condition (case C), a 2.5cm box length gives a more uniform cladding temperature distribution than the 2.4cm case, but the coolant temperature is much more uniform for 2.4cm.

Case A (low coolant inlet temperature) shows a cladding temperature spreading of about 30°C for 2.4 cm whereas almost no spreading is visible for 2.5cm (p. 10). The coolant temperature spreading is much more uniform for 2.4cm box length than for 2.5cm.

Going to much higher coolant inlet temperatures (case B), the uniformity for both coolant and cladding temperature is much more valid for 2.4cm side length than for 2.5cm.

From this analysis, it was recommended that the inner side length of the core barrel box be increased in length from 2.3 to 2.4cm. This length provides the best results in terms of a uniform cladding and coolant temperature distribution (in the order of 20°C) for the cases under consideration, especially for the ones for which high temperatures are expected (cases B and E).

A revised cross section of the heat transfer test section with the 2.4 cm. core barrel side length is shown in Figure 25.

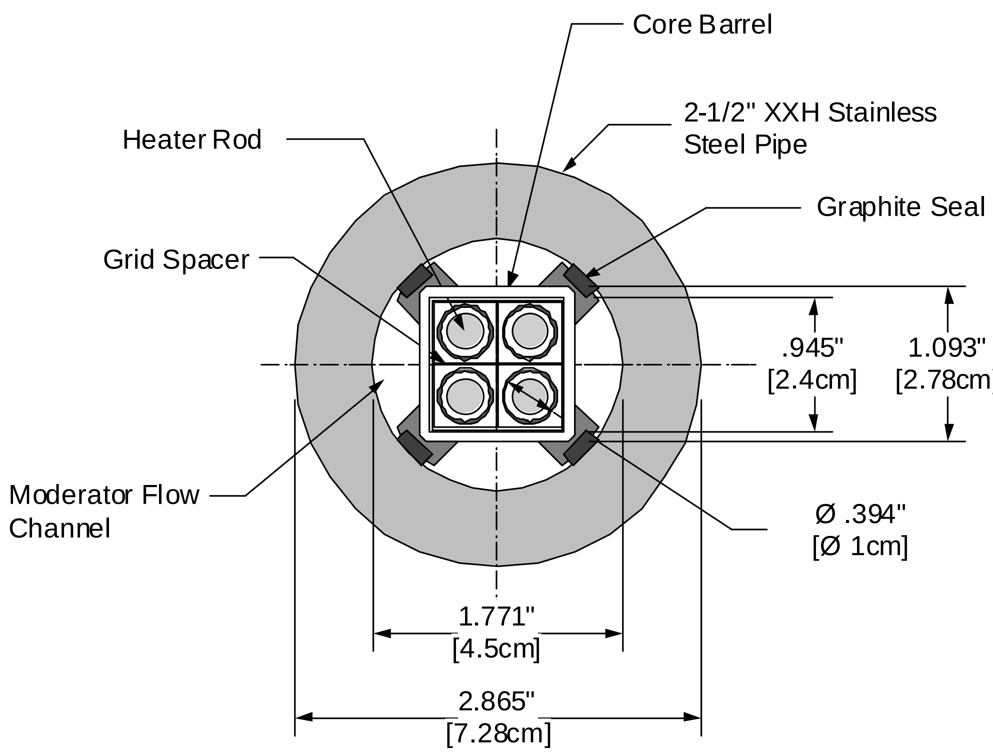


Figure 25. Test section cross section with revised core barrel dimension.

Fuel Rod Simulator

Electrically heated rods have been used successfully to simulate nuclear fuel rods in experimental facilities throughout the world for many years. The number of rods and the heated length of experimental electrically heated bundles have been limited only by available funds and the amount of electrical power available at the research facility.

Heating of the fuel rod simulators has generally been accomplished using two methods referred to as direct or indirect heating.

In directly heated rods, the heat is generated by joule heating in a metallic tube which forms the outer surface of the heater. A variable axial power density can be achieved by varying the thickness if the tube over the length of the heated portion of the heater rod. This type of heating is preferred in those experiments where control of rapidly changing surface heat flux is important to the phenomena being investigated. Measurement of the rod surface temperature using thermocouples is somewhat complicated by the fact that current is flowing in the material to which the thermocouples are attached.

In the indirectly heated fuel rod simulator a filament, wound from high electrical resistive wire or machined from a thin tube, is placed inside a tube that forms the outer surface of the heater rod. Heating is again by joule heating of the filament. High temperature powdered insulation is placed and compacted to fill the space inside the outer tube that is not occupied by the filament. An axial power profile can be achieved by controlling the number of turns per unit length of the filament. Thermocouples are attached to or pressed against the inside of the outer tube and exit the end of the heater rod. The surface thermal response to changes in the generated power is obviously slower than the direct heated rod, but is adequate for steady state conditions or slower transients.

At the design review meeting held at Erlangen it was decided that for the supercritical water test that indirectly heated fuel rod simulators should be used. Two methods were proposed for the construction of the rods, the primary difference is in the way the thermocouples were incorporated into the heater rod.

What will be called concept A is shown in Figure 26. In this concept the resistance element along with the insulation is swaged inside an inner sleeve. The inner sleeve is then machined with longitudinal groves in which the thermocouples are placed. A thinner outer sheath in then swaged around the assembly the hold the thermocouples in place and achieve the desired outer diameter. The machined groves would be at 45° spacing around the rod providing for a maximum of 8 thermocouples per rod if the leads were routed out the top only. A maximum of three thermocouples can be placed in the same azimuthal position at different elevations if some of the groves were machined part way around the rod. Figure 27 shows a cutaway view of concept A. The big advantage of concept A is the ability to precisely place the thermocouple junctions both axially and azimuthally. The downside of this concept is the tight tolerances required on the thermocouple diameter and the groove dimensions to ensure a good contact between the thermocouple and the outer sheath.

Fuel rod simulator concept B is shown in Figure 28. In this concept the resistance element, the thermocouples and the insulator are swaged together in a single sheath. The thermocouples tend to have a more consistent contact between the thermocouple and the sheath, however, the location of the thermocouple can not be controlled nearly as well as in concept A.

It was the decision of the design review group to use fuel rod simulator design concept A for the SCW heat transfer test section primarily because of the need to precisely position the thermocouples.

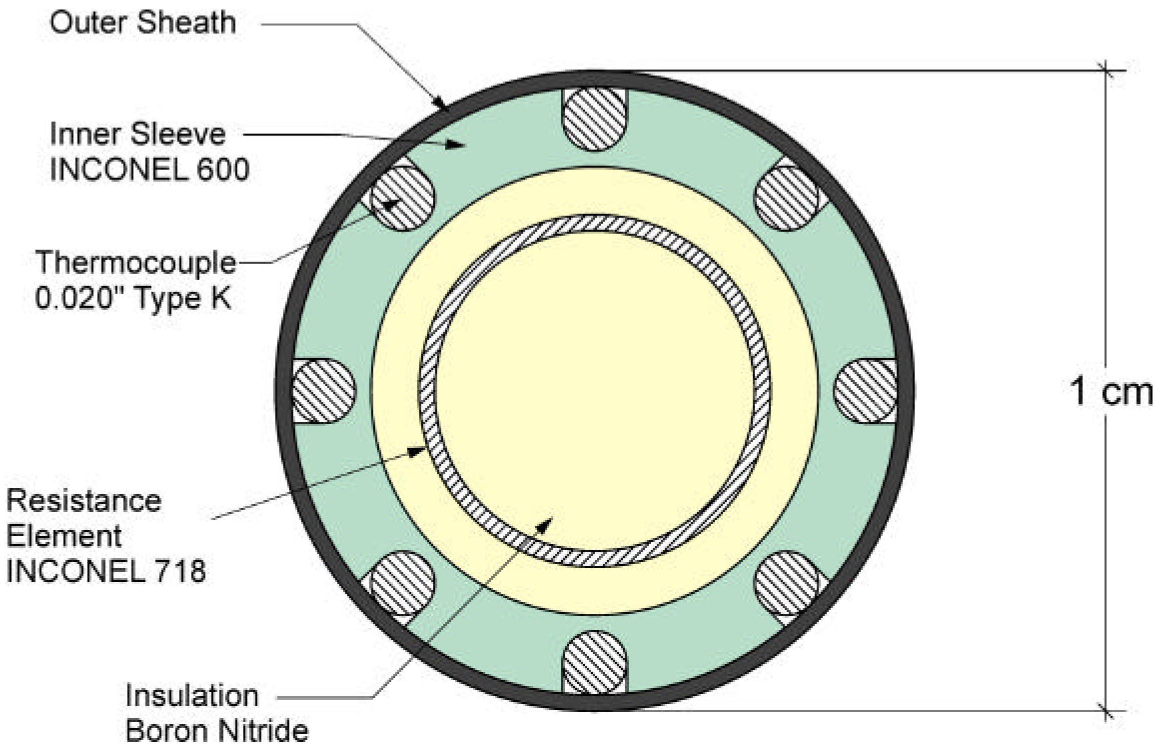


Figure 26. Cross section of fuel rod simulator Concept A

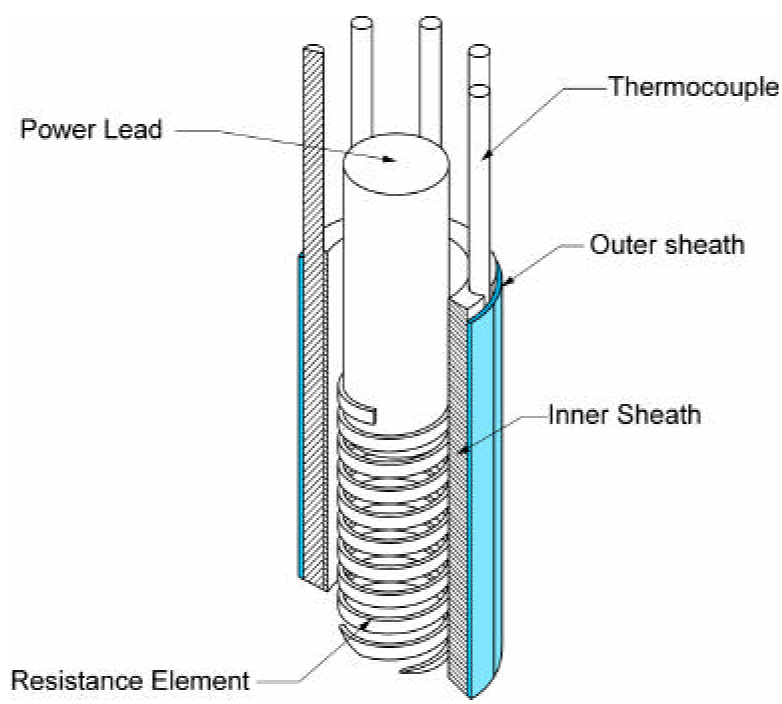


Figure 27. Cutaway of fuel rod simulator Concept A

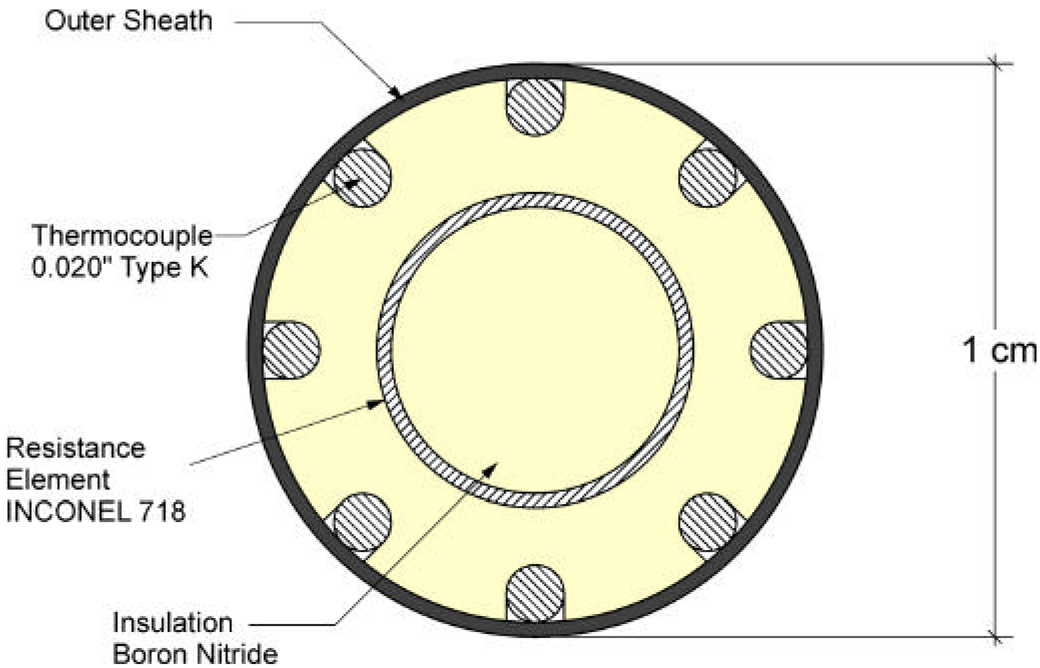


Figure 28. Cross section of fuel rod simulator Concept B.

The design parameters for the heat transfer test section fuel rod simulators are summarized in Table 4.

The heater rods extend through the top of the test section and are connected to power leads from the Benson Loop outside of the pressure boundary. Because the heater rods have such a small diameter and small pitch, it is not possible to seal each heater rod individually with a threaded compression fitting. The four rods will be brazed into a stainless steel block and the block will then be sealed to a specially machined Grayloc® blind hub using a metallic "O" ring and bolted compression cap as shown in Figure 29.

The positive Benson loop power leads will be connected to the heater rod electrode extensions using a copper block shown in Figures 29 and 30. A water cooled jacket may be required around the connection block to prevent heat buildup in the connection block. Calculations are pending.

The negative power lead connection to the heater rods is made inside the pressure boundary. This allows the heater rods to expand axially as they heat up during a test. A 2-1/2" Grayloc® cross is connected to the butt weld hub on the bottom of the main pressure pipe as shown in Figure 5. The core coolant enters through the bottom of the cross and the two cross legs are each used for passage of two flexible copper power leads from the negative side of the Benson Loop power supply. These leads are connected to the lower electrode extensions from the heater rods with a connection block similar to that used on the positive leads. This connection is shown in Figure 31.

The pressure seal for the power leads is made using a Conax® fitting with a two hole lava seal as shown in Figure 32. The fitting screws into a Grayloc® blind hub which has been drilled and threaded and attaches to the Grayloc® cross.

Table 4. Design Parameters for Fuel Rod Simulator

Number of Rods in Test Section	4
Rod Pitch/Diameter	1.15
Rod Diameter	0.394 in (1.0 cm)
Total Rod Length	108 in (374.32 cm)
Heated Length	39.37 in (100 cm)
Electrode Extension, top	1.78 in (4.54 cm)
Electrode Extension bottom	1.19 in (3.02 cm)
Maximum Heat Flux	1500 (kW/m²)
Maximum Power/Rod	47 kW
Maximum Voltage	220 volt DC
Maximum Current	214 amp
No. Thermocouples/Rod	8

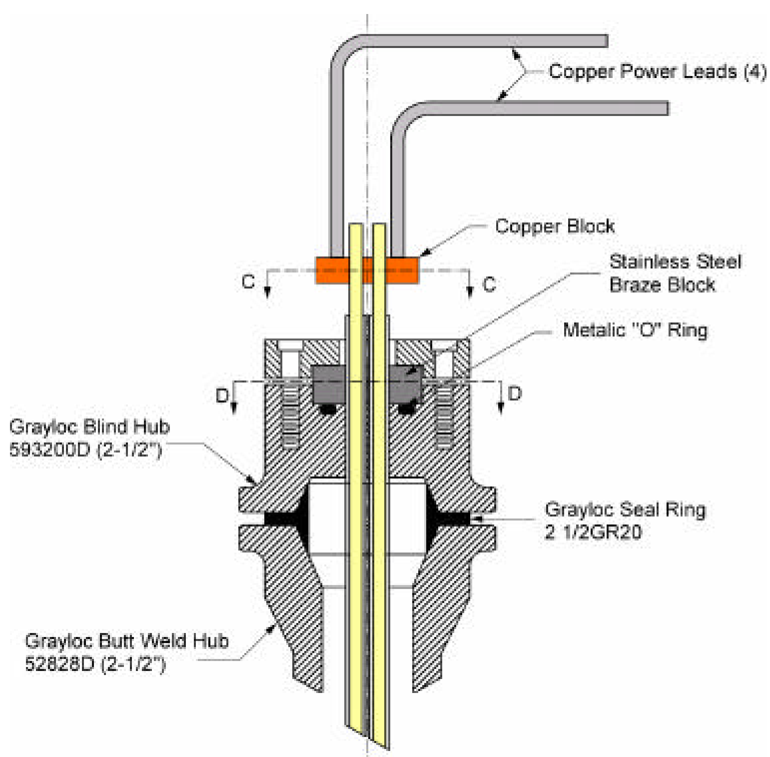


Figure 29. Heater rod upper penetration.

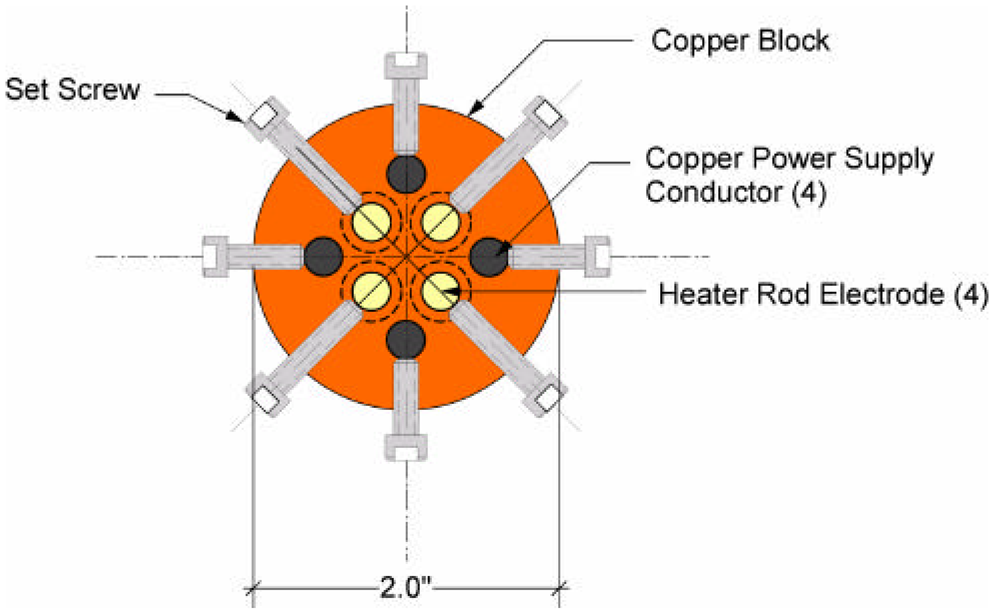


Figure 30. SECTION C-C electrode connector block.

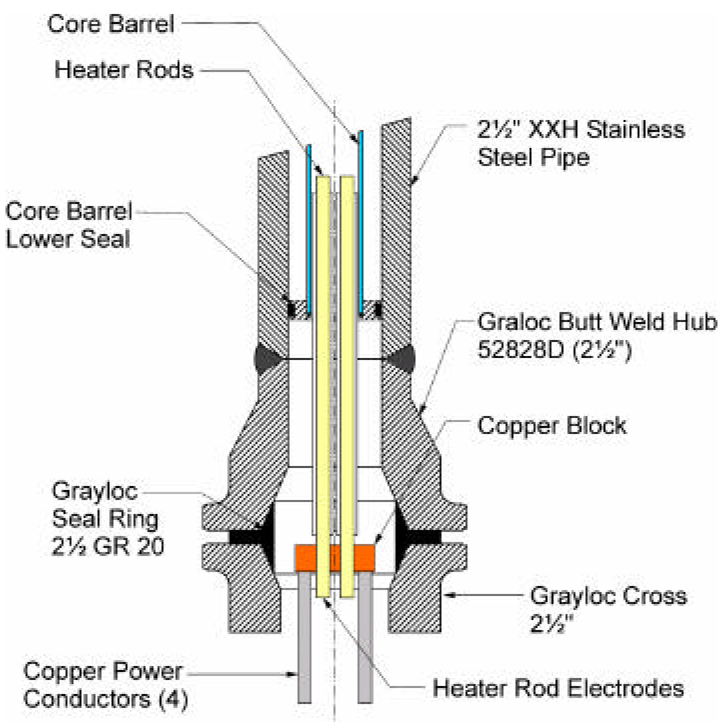


Figure 31. Lower power lead connection

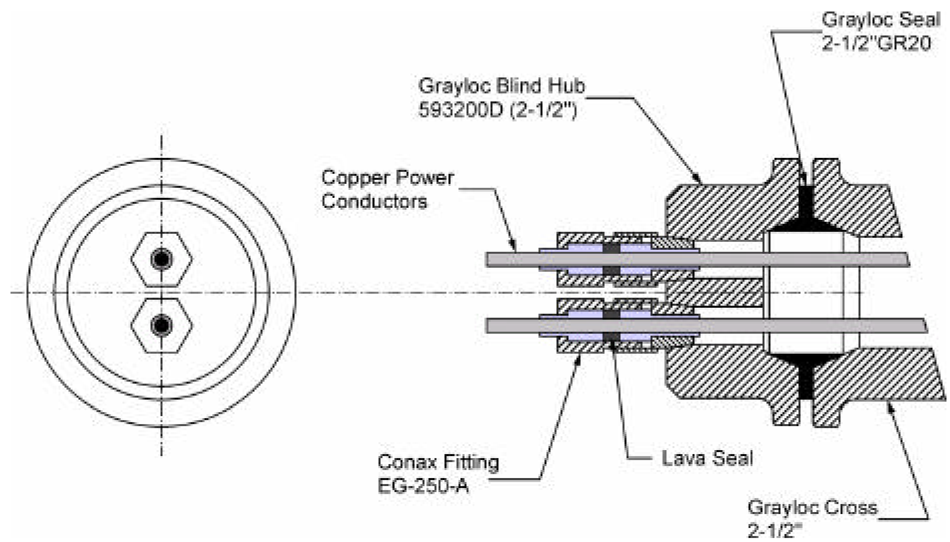


Figure 32. Negative power lead pressure seal.

A total of eight thermocouples can be located in each heater rod. The thermocouple lead wires exit the top of the heater at 45 degree azimuthal increments just under the outer sheath. It is possible to cross from one azimuthal grove to an adjacent grove with the thermocouple lead wires, making it possible to locate up to three thermocouples in the same azimuthal location at three different elevations.

Based on the Karlsruhe analysis of Himmel & Schulenberg[3], which concluded that more than three spacer grids would be required to prevent the heater rods from touching. Five grid spacers will be used spaced at 25 cm. apart over the 100 cm. heated length.

Figure 33 shows the orientation of the heater rods and the thermocouples used in this design. Figure 34 shows the proposed elevation and azimuthal location for each thermocouple for each of the four heater rods.

Fourteen thermocouples have been placed at potential hot spots on the heater rod surface and are intended to provide information for the protection of the heater rod integrity. The Karlsruhe analysis performed, in Ref. 2 to optimize the size of the core barrel showed calculated cladding temperatures for six cases for each of three different box sizes. For Case B, the predicted heater rod temperatures were significantly higher than any of the other cases. For the optimum box size of 2.4 cm. the maximum cladding temperatures for Case B occurred at the exit of the heated portion of the heater rods and the temperatures were very uniform around the circumference of the heater rod. This suggests that a temperature peak could occur at any azimuthal location on the heater rod at the end of the heated length. It is proposed then that all eight thermocouples be placed at the elevation of the end of the heated length, at the exit of the grid spacer for heater rod "A" as shown in Figures 1 and 2. Additional protection thermocouples are proposed to be placed on heater rod "B" at the exit of the top three grid spacers at the zero and 180 degree azimuthal locations.

The balance of the thermocouples are intended to be used primarily for accumulation of heat transfer data. On heater rod "C" there are two sets of three thermocouples at azimuthal locations zero and 180 degrees, equally spaced axially between the top two spacer grids. The other two thermocouples on that rod are placed at somewhat arbitrary locations closer to the beginning of the heated length. To investigate the heat transfer around the circumference of the heater rod away from the spacer grid, it is proposed that all eight thermocouples on rod "D" be located at the midpoint of the upper two spacer grids and at each of the eight azimuthal locations.

As more analysis becomes available it is anticipated that some of the proposed locations will be changed to allow investigation of phenomena revealed through the analysis. Input from other program participants is certainly encouraged.

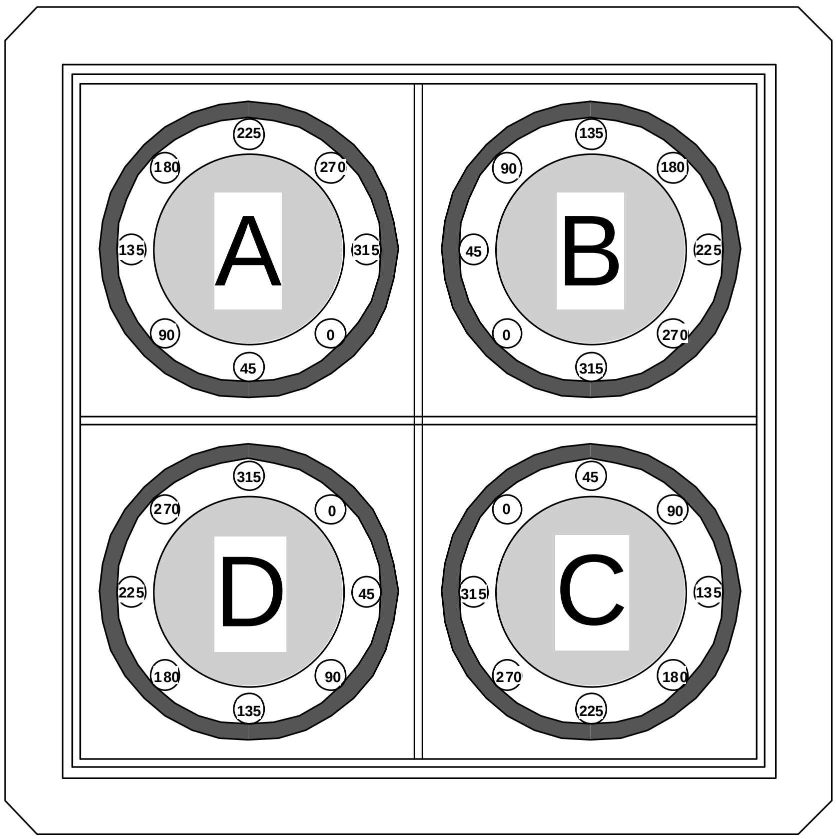


Figure 33. Heater rod and thermocouple orientation for the SCW heat transfer test section.

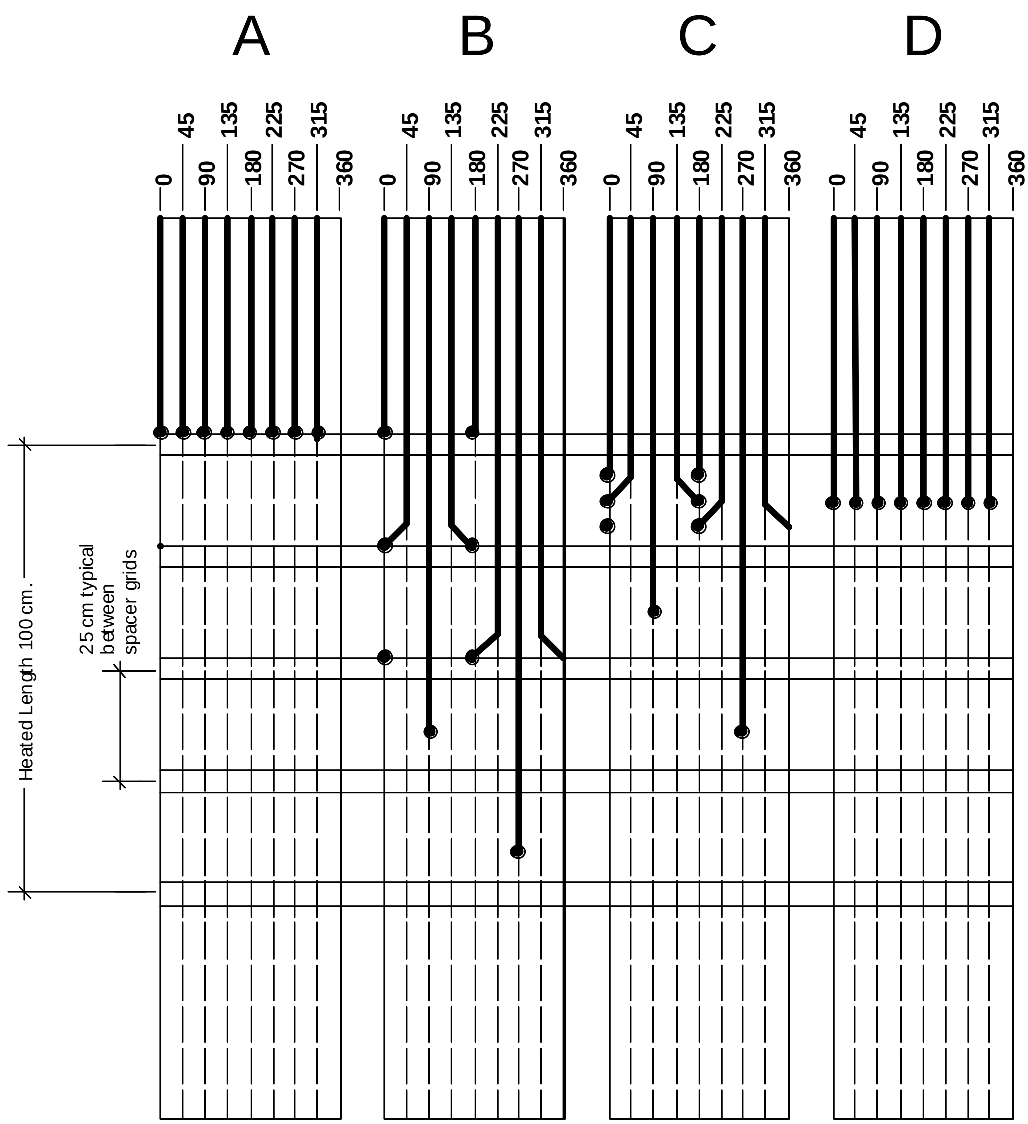


Figure 34. Proposed thermocouple locations for the SCW heat transfer test section.

Grid Spacers

Grid spacers are required in the heated length of the test section to keep the heater rods from bowing and deforming the flow channels which would lead to hot spots in the heaters. A typical grid spacer is shown in Figure 35. They are made from relatively thin metal with fingers formed in the sides to apply point loads to the heater rods and are assembled to create a box around the heater rod bundle.

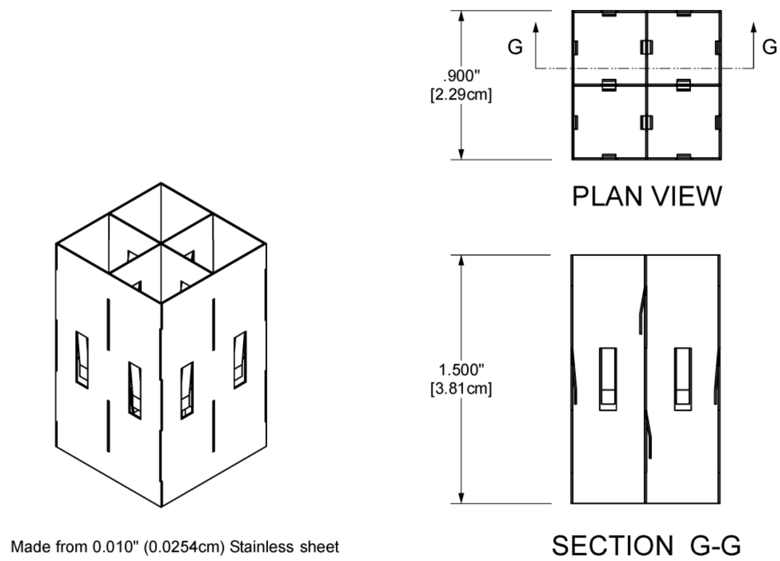


Figure 35. Typical grid spacer.

When this design was undertaken, the review group recommended a maximum spacing of 50 cm between grid spacers. As an action item from the March review meeting, the participants from Forschungszentrum Karlsruhe were assigned to calculate the bending of the heater rods and to recommend a maximum spacing for the grid spacers. The requested analysis was completed by Himmel and Schulenberg3 and was based on the following assumptions:

- symmetric temperature distribution of the 4 fuel pins
- linear temperature gradient in diagonal direction on each fuel pin
- constant temperature distribution in vertical direction between two spacers
- S-shape of the bended pin, causing no bending moment at the spacers
- linear elastic deformations only
- no thermal stresses reducing the thermal deflection
- thermal expansion coefficient $a_T = 1{,}4 * 10^{-5} \frac{1}{K}$.

Their results are summarized in Figure 36. This figure shows the relationship between the spacing between grid spacers and the maximum temperature gradient across a heater rod that can be tolerated before contact between heater rods is expected. The thermal analysis reported in Reference 2 showed that by increasing the core barrel side length from 2.3 to 2.4 cm that a temperature difference across a heater rod would be 20°C or less. This would indicate that a grid spacer spacing of 25 cm. would be appropriate for the heat transfer test section.

One additional recommendation of the review committee was that the spacer grids have mixing vanes incorporated into the outlet of each grid spacer to promote mixing in the flow channels.

No additional design work has been done by INL on the grid spacers because Framtome ANP volunteered to design and fabricate the grid spacers for the heat transfer test section.

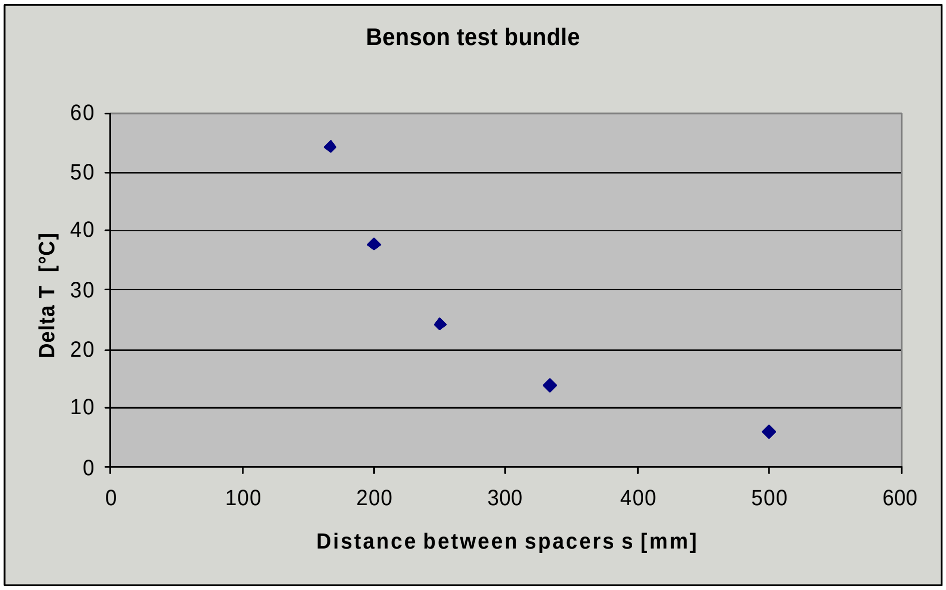


Figure 36. Results from heater rod bending analysis.

Moderator Flow

There are four channels within the SCW heart transfer test section defined on the inside by the core barrel and on the outside by the pressure boundary pipe which are used to simulate the moderator flow channels in a SCWR.

The moderator flow enters the test section above the heated portion of the core and flows downward through the four channels and exits below the heated portion of the core. Access to the flow channels within the test section for both the inlet and outlet is via Grayloc® nipples which are welded to the pressure boundary pipe in each of the four quadrants as shown in Figure 37. Piping from the Benson loop is connected to the nipples using Grayloc® hubs.

The inlet temperature and flowrate for each of the four moderator flow channels is controlled independently in the Benson loop.

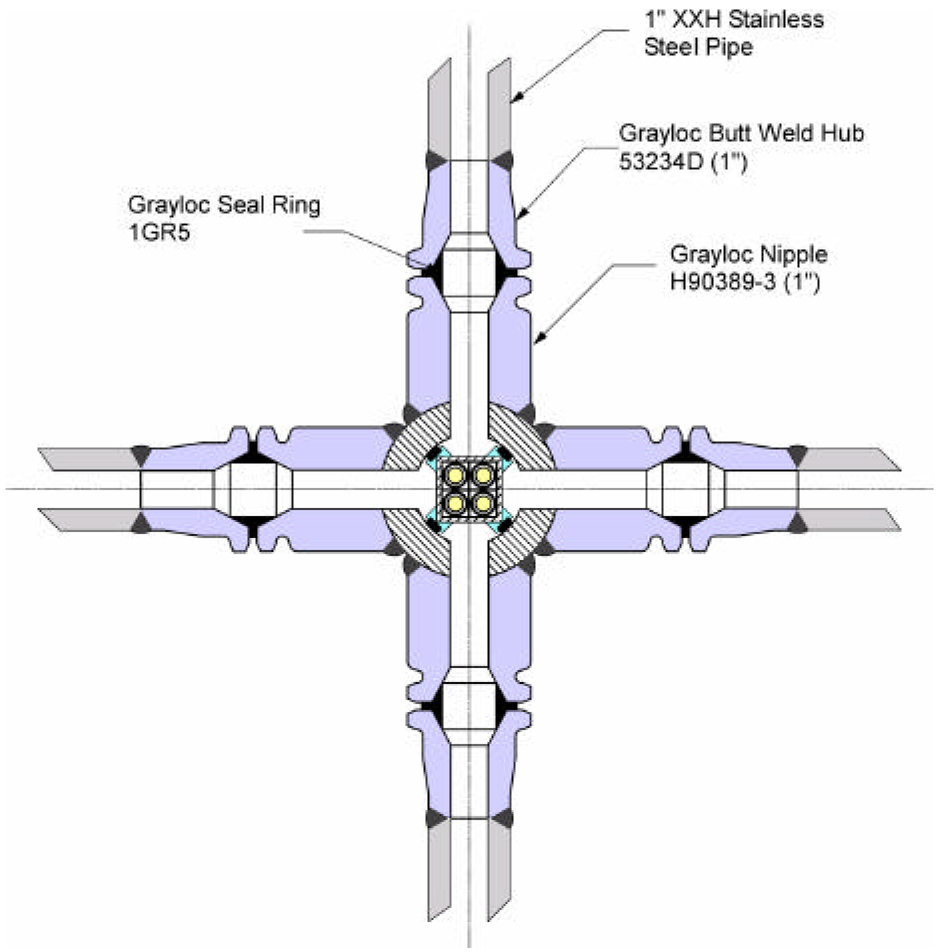


Figure 37. Moderator flow inlet and outlet connection details.

Instrumentation

Instrumentation for the SCW heat transfer test section includes the following:

1. Temperature, pressure, and mass flowrate for core inlet coolant
2. Core outlet coolant temperature
3. Inlet temperature, pressure, and mass flowrate for each of the four moderator flow channels
4. Outlet temperature and mass flowrate for each of the four moderator flow channels
5. Heater rod voltage and current
6. Eight cladding temperatures for each heater rod
7. Seven pressure measurements at selected elevations inside the core
8. Core barrel wall temperature at five axial locations
9. Core fluid temperature at three axial locations

The instrumentation for items 1 thru 5 above is included in the Benson loop and is not discussed in this report. The heater rod cladding temperatures (item 6) were discussed in the Heater Rod section of this report.

Pressure measurements inside the core will be made near the inlet to the heated length, just below the middle grid spacer, at the outlet of the middle grid spacer, and at two inch increments above the middle grid spacer. Access to the core flow channel for the pressure sense line is shown in Figure 38.

A 1/8" Swagelok® male connector is cut in half and the tube end is welded to the outside of the core barrel at the desired location. A 1/16" hole is drilled through the core barrel in the through the center of the Swagelok® fitting. A 1-1/16" hole is drilled in the pressure boundary piping opposite the fitting that was welded to the core barrel. The large hole is required in to provide access for a tool to tighten the Swagelok® nut over the connector. A one inch Threadolet® is welded to the pressure boundary pipe centered over the previously drilled hole.

After the core barrel is in place insert a short piece of 1/8" sense line tubing into the Swagelok® fitting and tighten. Slip a 1" x ¼" reducer bushing over the open end of the sense line and screw tightly into the Threadolet®. Slide the Conax fitting over the open end of the sense line and tighten the body of the Conax fitting into the reducer, then tighten the cap of the Conax fitting. The open end of the sense line tubing is then attached to the line going to the pressure transducer.

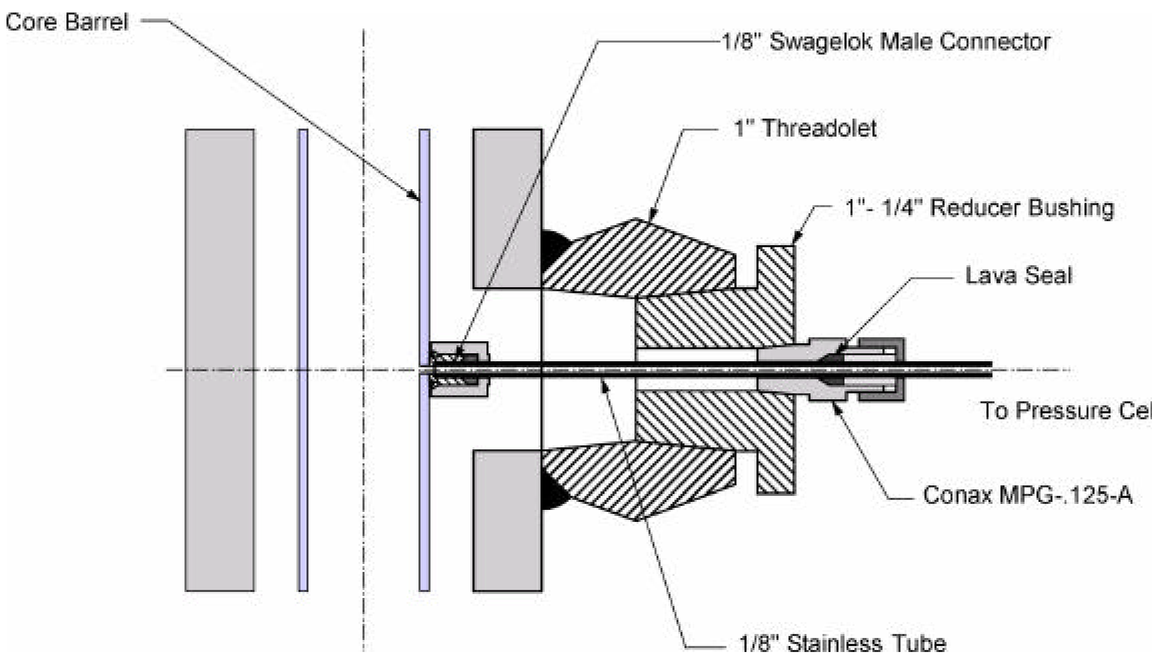


Figure 38. Pressure sense line access and connection diagram.

The core barrel wall temperatures are made by spot welding a 1/16" stainless steel sheathed type K thermocouple to the core barrel wall. The thermocouple leads go up the moderator channel and through holes drilled through the core barrel flange (Figure 7) and are threaded out through the reducing cross near the top of the test section. The core fluid temperature thermocouples are welded into holes in the core barrel such that the tip of the thermocouple just enters the flow stream. They exit in a manner similar to the core barrel wall thermocouples. The thermocouples are seal brazed where they pass through the core barrel flange.

The pressure boundary seal for the thermocouples is shown in Figure 39. A Grayloc® blind hub is drilled and tapped to accept an 8 hole Conax fitting and attached to the Grayloc® cross. The thermocouples are threaded through the Conax fitting and sealed as the cap is tightened.

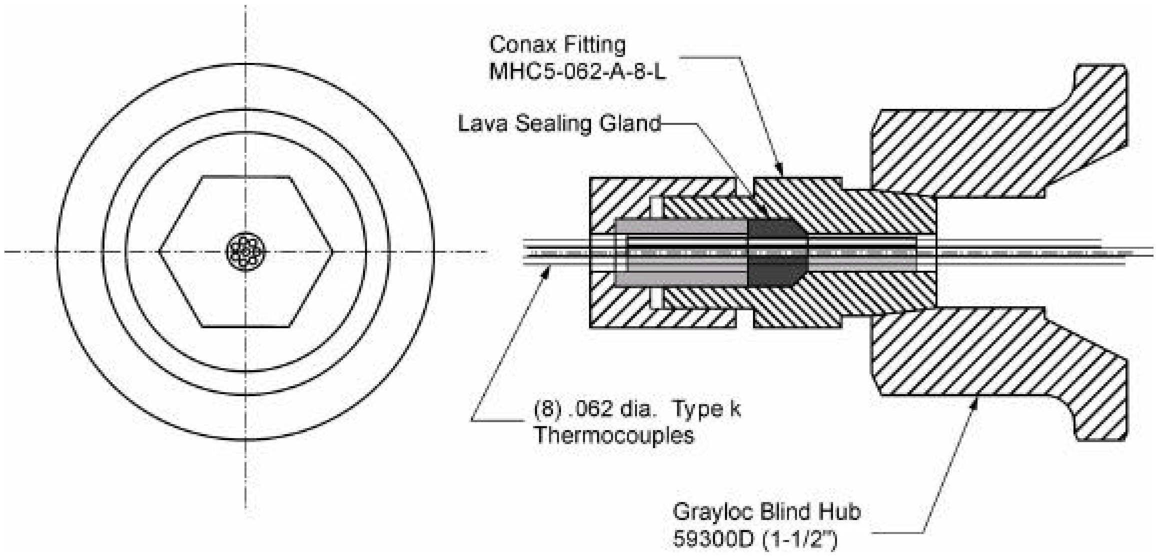


Figure 39. Thermocouple pressure seal.

5. References

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1. H. Schmidt, W. Köhler, and W. Kastner, High-Pressure Test Facility – 25 Years of Operation, Framatome ANP GmbH, March 2001, An extended version of the publication with the same title in VGB Power Tech, 06/2000, pp. 25-31.
2. Waata, C. L., Opimization of the Box Size of the BENSON Test Section, FZK, April, 2005, Private communication.
3. Himmel, S, and Schulenberg, T., Thermal Deflection of the Fuel Pins in the BENSON Test Rig, May, 2005, Private communication.

APPENDIX A

SUPERCRITICAL WATER HEAT TRANSFER TEST SECTION COMPONENT ANALYSIS

Michael E Nitzel

Introduction

The supercritical water heat transfer test section (SCWHTTS) is generally comprised of piping components. As such, the American Society of Mechanical Engineers (ASME) Code for Pressure Piping, B31.1-2004[1], was determined to be the applicable national consensus code to be used in the structural evaluation of the piping components.

The overall layout of the test section can be seen in Figure A-1. The remainder of this section of the report is structured using headings similar to those found in a standard INL structural/stress analysis report. The intent is that this topic organization will provide the reader with a logical progression through the evaluation process that is normally used in the structural analysis of these types of systems, structures, and components (SSCs).

Scope

The scope of this evaluation is expected to change somewhat as the overall system design evolves; however, preliminary calculations are underway to address the following components:

1. Evaluation of the 2 ½-in pipe comprising the test section
2. Pressure tap to pipe connections
3. Moderator inlet piping connections
4. Moderator outlet piping connections
5. Bolt torque requirements for the test section 2 ½-in flange connection

6. Standard vendor components will also be examined to verify that expected operating conditions (e.g., temperature and pressure) are within the vendor's limitations. These components include:

    - 2 ½-in inlet cross
    - 2 ½-in X 1 ½ outlet cross
    - 1-in nipples used in connections of the moderator inlet and outlet piping
    - Connection fittings (e.g., Grayloc hubs) used in the inlet and outlet connections

Other components may be included in the analytical scope as the design evolves and consultations with the project personnel identify additional needs.

Safety Category

In observance of INL standard practice, a safety category is assigned to all SSCs. In consultation with project personnel, the SCWHTTS has been defined as Commercial Grade.

Natural Phenomena Hazards (NPH) Performance Category (PC)

Standard practice for the design and/or evaluation of SSCs within the United States Department of Energy (DOE) system is to include consideration of natural phenomena loading conditions where appropriate. Natural phenomena loads include earthquakes, winds, floods, and any other natural phenomena that may be applicable specific locations or facilities. Based on the relatively limited duration of test run periods, project personnel have directed that natural phenomena hazard loads are not applicable to the evaluation of the SCWHTTS.

Structure, System, or Component (SSC) Description

The SCWHTTS is generally constructed using stainless steel piping and standard components and fittings available from piping industry vendors. As indicated, there are a limited number of fittings that will be specially modified to accommodate heater lines and instrumentation. The overall arrangement of the SCWHTTS is shown in Figure A-1.

Materials

Materials listed as acceptable in the appropriate sections of the B31.1 Code or, possibly, Section II of the ASME Code[2] will be used as the source of material properties included in stress analyses. Typical values for the stainless steels expected to be used in this project are summarized below:

$E \equiv 22.6\ (10^6)$ psi [Modulus of elasticity at 1022°F (550°C)]
$S \equiv 7140$ psi [allowable stress at 1022°F (550°C)]
$a \equiv 10.4\ (10^{-6})$ in/in/°F [mean coefficient of thermal expansion at 1022°F (550°C)]

Loads

The loads considered for the piping analyses described herein include weight, internal pressure, and thermal expansion. As previously mentioned, no natural phenomena loads are planned to be included in the structural evaluation.

Assumptions

In general, assumptions used in the course of the stress analyses are discussed at the point of their application. Such detailed discussions will appear in the following sections as applicable and also, as appropriate, within the calculations contained in specific analysis reports that will be prepared for the project.

Generic assumptions used in completion of the analyses are listed below:

1. All piping and components are insulated. Weight of insulating materials will be included in the appropriate load case considered in the piping system calculations.
2. All systems are filled with water. Weight of internal fluid will be included in the appropriate load case considered in the piping system calculations.
3. Operating temperatures and pressures consistent with those specified by the project personnel will be used.
4. Actual weights of fittings incorporated in the piping system will be used where available. Otherwise, reasonable estimates will be made and utilized in the analyses.
5. The weight of the bolts and nuts used in the flange joints will be obtained from commercial data obtained from the vendor’s web site if possible. Otherwise, estimates based on other industry accepted sources will be used.
6. The stress range reduction factor, f, used to calculate the allowable stress range for expansion stresses is based on 7,000 full temperature cycles as listed in Table 102.3.2(c) in the B31.1 Code. This is a reasonable assumption based upon the limited number of temperature cycles that the SCWHTTS piping is expected to experience.
7. Any other assumptions will be stated and justified at the point of their use.

Acceptance Criteria

The ASME B31.1 Power Piping Code will be used to define acceptance criteria for the SCWHTTS piping.

Calculations

Minimum Thickness Check

The acceptance criteria require verification that the piping wall thickness is greater than the minimum value required for retention of the design pressure. The minimum required wall thickness is the greater value calculated using the following equations:

$$t_m = \frac{PD_o}{2(SE + Py)} + A$$ (Equation 3, Paragraph 104.1.2, Reference 1)

$$t_m = \frac{Pd + 2SEA + 2yPA}{2(SE + Py - P)}$$ (Equation 3A, Paragraph 104.1.2, Reference 1)

Where:

t_m = minimum required wall thickness
P = internal design pressure
d = inside diameter of pipe
D_o = outside diameter of pipe
S = allowable stress at the design temperature
SE = allowable stress at the design temperature adjusted for joint or casting quality
y = 0.4 (per Code)
A = corrosion allowance

The minimum thickness check calculation results for the piping will be summarized in the final analysis report.

No corrosion allowance was specified for the piping or components. Thus, the minimum wall thickness calculations were performed assuming no corrosion allowance. Considering the relatively limited operational lifetime planned for the system, it is reasonable to assume negligible corrosion.

Standard fittings (e.g., weldolets, Grayloc hubs, etc.) are included in the system design to connect the SCWHTTS with ancillary piping and instrumentation. Evaluation is ongoing to verify that these fittings meet the B31.1 requirements and that the required area of reinforcement is available at the connections as required by Paragraph 104.3.1 of Reference 1.

Description Of Pipestress Computer Code

The Pipestress computer program performs linear elastic analyses of three-dimensional piping systems subjected to a variety of loading conditions such as deadweight, thermal loads, support displacements, static forces, time-history forces and accelerations, and seismic response spectra. This program will be used to perform any computerized finite element piping analyses that are performed at the INL for the SCWHTTS project. Pipestress can analyze a large number of load types either singly or in combination and compare the analytical results to a variety of industry standard codes such as the ASME Boiler and Pressure Vessel Code (Class 1, 2, and 3; several Code editions), ANSI/ASME B31.1, ANSI/ASME B31.3, etc.

The program has been verified and validated as required by INL Management Control Procedure (MCP)-3039 (Analysis Software Control).

Design Conditions

Equation 11A in Paragraph 104.8.1 of the B31.1 Code is the governing expression used for the consideration of design conditions. Equation 11A considers the effects of weight, design pressure, and any other sustained mechanical loads. The Pipestress computer code tabulates these stresses at each node point in the finite-element piping model.

Occasional Loading Conditions

Equation 12A in Paragraph 104.8.2 of the B31.1 Code (Reference 1) is the governing expression used for the consideration of occasional loads such as natural phenomena loading. As previously mentioned, no such loads have been specified for the SCWHTTS.

Thermal Expansion

The requirements of Equation 13A in Paragraph 104.8.3 of the B31.1 Code (Reference 1) must be met when considering thermal expansion. This equation considers the range of moment loading die to thermal expansion and anchorage effects. The Pipestress computer code tabulates these stresses at each node point in the finite-element piping model.

Supports Evaluation

The exact layout and configuration of the piping supports that will be attached to the overall test system are not known at this time. Structural analyses will be performed using standard structural analysis methods which may include a mixture of classical "hand" methods and computerized finite element analyses as appropriate. Due to the thermal expansion effects that are expected as the system heats up from room temperature to the expected operation temperature of approximately 1020°F (550°C), it is likely that the majority of supports will be spring hanger type supports that will provide the needed flexibility. Support loads will be obtained from the piping analysis of the overall test system and then utilized to qualify the individual support assemblies. The piping support qualification calculations will consider the effects of weight, thermal expansion, and pressure.

Conclusions

As previously noted, final system structural analyses have not been completed at this time and the analytical effort is ongoing. Preliminary results indicate that material selection is extremely important due to the high operating temperature of the system. Such issues are being addressed as they arise and solutions are being incorporated into the system design.

Recommendations

Thus far, the piping component analyses have only identified the recommendation that a higher strength stainless steel material such as SA-312 TP316N will be needed. As mentioned, the current analyses are considered preliminary and will be finalized as additional work is completed.

References

1. ANSI/ASME B31.1, “Power Piping,” American Society of Mechanical Engineers, 2004 Edition.

2. American Society of Mechanical Engineers, “Boiler and Pressure Vessel Code, Section II, Part D Properties), 2004 Edition.

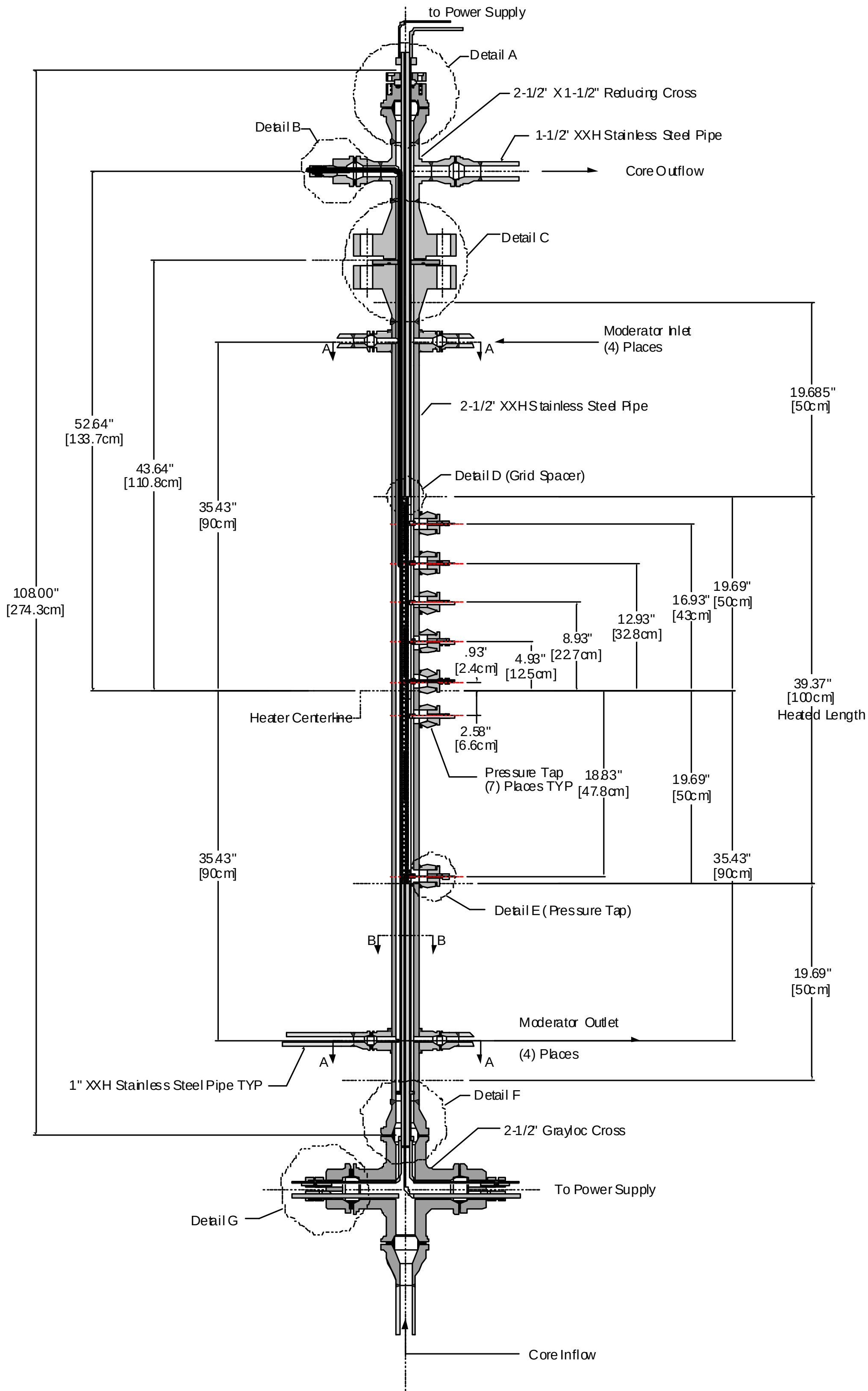

Figure A-1. Supercritical Water Heat Transfer Test Section Layout.